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A STUDY OF VISUAL FUNCTION AND ACQUIRED DYSCHROMATOPSIAS

by

Peter Alan Aspinall

Ph.D. Thesis
University of Edinburgh
February, 1973.

A B S T R A C T

This study examines the nature of several tests of colour vision and of general visual function. Psychophysical methods are reviewed which are applicable to all visual function tests. This is followed by a discussion of the normal visual process with particular emphasis on scotopic, photopic and colour discrimination mechanisms. Acquired Dyschromatopsias are discussed against the background of normal colour vision and congenital colour vision defects. Two general divisions of acquired dyschromatopsia are made, namely those with a physiological basis and those of clinical origin. Tests of colour vision and of general visual function are developed and assessed. Norms for the ageing processes are established for each test and the tests are applied to a variety of clinical dyschromatopsias.

A C K N O W L E D G E M E N T S

The writer would like especially to thank -

The W.H. Ross Foundation (Scotland) for the generous financing of this study.

Professor G.I. Scott and Professor R. Lakowski for their initiation of this project.

Mrs. V. Menzies and Mrs. D. Mitchelson for typing.

Mr. O. Asiyanbola for his assistance throughout the project.

Mr. A. McDonald for his help with diagrams.

C O N T E N T S

I INTRODUCTION

Tests of visual function are devised to provide information about the nature or the state of the visual system. The tests of particular interest in this study are those requiring observer participation, and they rest on the assumption that there is a certain correspondence between the physical characteristics of a stimulus and the resulting sensation. Because sensation is an internal psychological event, evidence about what is seen is indirect and based upon the subjective reports of an observer. Inferences about the visual system itself are made possible by quantifying the stimuli presented to the observer, and by restricting the permissable categories of his response. The generic term for this class of experiment is psychophysics. The principal psychophysical tests used in this study are those requiring an observer to respond to a light stimulus which may be varied in intensity and wavelength. The use of these particular stimulus variables places the tests in the general category of 'tests of colour vision'.

The purpose of this study is the quantification of functional variations in vision. The detection of functional variations is clearly dependent upon the sensitivity of a visual function test. This sensitivity can be increased by:-a.) the selection and control of/

of an appropriate method of measurement, and b.) the selection of stimuli which are most effective in reflecting changes in physiological mechanisms. Both factors enable physiological variations to be most effectively sampled by a psychophysical test. With this aim in view, the first part of the study deals with an examination of psychophysical methods. This is followed by a description of the nature of the visual system using evidence from psychophysics and from other disciplines. This provides a necessary background for an assessment of the state of the visual system. The state may change and give rise to functional variations in vision. These may occur due to clinical processes or they may occur due to normal physiological processes. The emphasis of the present study is directed towards the application of psychophysical tests in the clinical situation. However, before it is possible to assess changes in function due to clinical processes, it is necessary to know the types and range of physiological variation in normal vision. This information may be provided in two different ways - firstly, from general findings on the nature of the visual system; secondly, from the results obtained on any visual function test of visual sensitivity and from the variation in visual sensitivity occurring in a normal population. Once the variation within a normal population has been defined for each test in statistical/

statistical terms, the limits of normality can be established. This provides a basis for the assessment of both normal and abnormal visual mechanisms. In this study a battery of visual function tests has been devised, based upon knowledge of the different physiological mechanisms underlying visual performance. Some tests in the battery are new and have been developed along the lines outlined above. Other existing tests in the battery have been modified towards this end. The complete test battery provides information on different aspects of visual function within the present stimulus framework. One of the principal stimulus variables is wavelength so that the colour discrimination mechanisms of an observer can be studied.

It is a well known fact that the colour vision of certain individuals differs radically from that of the great majority of observers. Such individuals are said to have a colour vision defect or anomaly. Since the 17th century the congenital dyschromatopsias have been described. These are inherited colour vision defects which are present at birth and which do not change in the course of a lifetime. They reflect basic differences in the underlying mechanisms for colour discrimination. These defects are to be contrasted with the acquired dyschromatopsias, which are colour vision defects which may develop and change within the life span of an individual. In acquired dyschromatopsias it/

it is generally assumed that at some point in time the individual had a normal visual system, so that the dyschromatopsias represent subsequent deviations from normal vision.

Early studies on the acquired colour anomalies in vision were undertaken towards the end of the 19th century by German research workers who initiated studies on the physiology of vision. These studies including works by Helmholtz, Koenig, V. Kries , Koellner and Nagel,were summarised by KOELLNER (1912). The recent revival of interest in acquired dyschromatopsias dates from the middle 1950's and has been reinforced recently by the formation of an international research group for the study of colour vision deficiencies. The general findings of the German school suggested four main reasons for tests of acquired dyschromatopsias in the clinical situation:

1. The tests are a sensitive index of vision and may give the earliest indication of pathological change.
2. Because they are sensitive to change they may give a measure of the state of the visual system which closely follows a disease process.
3. They enable quantification of the type of visual loss present so that for diagnostic purposes degrees of change in different mechanisms may be compared. /

compared.

4. The type of visual loss is associated with the site of pathological disturbance.

This latter point became formalised in "Koellner's Rule", KOELLNER (1912), which stated that lesions of the ganglion layers and the optic nerve produce red-green deficiencies whereas those in the receptor and other plexiform layers produce blue-yellow deficiencies. Although more recent studies recognised that certain qualifications to this rule were necessary (see page 109) the rationale for these tests remains the same, as can be seen from writings of recent authors. For instance, ZANEN (1953) has proposed the following axion, "When an absolute central scotoma has been found, it must have been possible at a certain moment of its evolution to detect a relative scotoma for colours and probably particularly at the start of the illness". Furthermore, Zanen suggests that the mechanisms causing deterioration in colour and in acuity are different, and that changes in colour perception frequently occur before those in acuity. Similarly, DUKE-ELDER (1968) says "The loss of colour perception frequently affords a delicate test for the detection of an early impairment of vision and in this event the greatest interest in the colour field arises. In these cases sensitivity to one colour may be lost preferentially. For example, loss of sensitivity for blue is an early change in nutritional disturbance/

disturbance of the retinal neural epithelium and therefore, is apparent in diseases of the choroid; conversely, a diminution of sensitivity to red and green precedes that for blue in diseases affecting the transmitting neural apparatus, for example, in optic nerve atrophy".

It is against this background that the present work is set. A study of acquired dyschromatopsias can provide complementary information on both normal and abnormal visual mechanisms. The first part of this report will deal with a comparison of psychophysical methods. Studies on normal vision will be presented to form a perspective for the studies on colour vision anomalies. Following the section on the development of tests the results are presented for different clinical populations. As this work was carried out in the context of a Retinal Function Unit, evidence from the clinical picture will be used where necessary as a basis for inter-correlations between tests and also to provide a fuller understanding of the nature of the observable changes.

II PSYCHOPHYSICAL METHODS

The methods and techniques necessary for an assessment of visual function have been developed during the last hundred years. The first attempts at its measurement and quantification were made by Gustav Fechner, who in 1860 published his "Psychophysics". This treatise was an experimental approach towards uniting the psychological with the physical world. Without recourse to metaphysical questions, or to the heated debate, which followed the publication of this treatise, as to whether sensation could or could not be measured, from an operational point of view the experiments were straightforward and consisted in measurements of "thresholds". A threshold was defined as a boundary separating stimuli which elicit one response from stimuli which elicit a different response. It was assumed to be a property of an observer. There were essentially two basic psychophysical questions:-

1. How intense must a stimulus be to be perceived?
2. What is the relationship between physical stimuli and the corresponding conscious sensation?

The first question led to an investigation of the absolute threshold. This was measured by increasing a stimulus along the physical continuum until the observer's response changed from "No, I do not see it" to "Yes, I/

I see it". The second question which is more complex, was formulated by an investigation of the differential threshold. Here two stimuli were adjusted until the observer perceived them as identical. One stimulus was then changed along a selected dimension until the observer first noticed a difference between the two stimuli. This point was reached when the observer's responses changed from "The stimuli are the same" to "The stimuli are different". The notion of the j.n.d. (just noticeable difference) was introduced as the threshold point.

The first problem which arose out of these experiments was that although the threshold was considered as a fixed boundary, responses to a constant stimulus were not themselves constant. This finding in itself did not invalidate the idea of a boundary, providing the boundary could shift in time from one moment to the next. But because of this, for practical purposes, a threshold was obtained from the average of a repeated series of measurements. The threshold became, therefore, a construct - a statistical point arbitrarily defined (usually at the 50% frequency of "Yes" or "Different" responses). In the determination of either the absolute, or the differential threshold, three principal psychophysical methods were used. These are now known as the three classical methods./

methods./

IIa) Classical Methods

The Method of Limits

This method employs a procedure whereby the physical dimension for which a threshold is required is changed in small consecutive steps. In determinations of the absolute visual threshold, a graded series of light intensities is chosen, ranging from light which is too dim to be seen, to light which can always be seen. Beginning at the lowest intensity, a stimulus flash is presented to the observer in an ascending order until the response changes from "Not seen" to "Seen". The intensity of light at either the last negative response or the first positive response, is taken as the threshold value. The order of presentation of the flash is then reversed, so that the response changes from "Yes" to "No" in the descending series of light intensities. The final threshold is determined by averaging the data obtained on a number of ascending and descending trials. The reason for the existence of ascending and descending trials, is an attempt to cancel out any constant errors which are present. For example, the "error of habituation" is the tendency to continue reporting "Yes", in a descending series or "No", in an ascending series. The "error of anticipation" is the opposite. An identical procedure applies for the determination of the differential threshold, in which the response is "Same" or "Different"/

"Different" as the stimuli are changed in consecutive steps.

The Method of Average Error

This method while applicable to both absolute and differential thresholds, has been most useful in studies of stimulus matches. The observer is required to adjust a variable stimulus until it matches a fixed standard stimulus. On alternative trials the variable stimulus is set at opposite ends of its range before the observer begins to "zero in" on the match. The average value of repeated individual matchings is taken as the matching or equivalent value. The difference between the equivalent setting, and the standard stimulus, gives the constant error in the measurement. The threshold value is obtained from the variability of the matches. For example, the standard deviation is assumed to be proportional to the difference threshold, and can be used to represent it. An alternative use of this method is to ask the subject to adjust the variable stimulus until it is just different from the standard. The difference between average deviation of the resultant settings and the standard is the differential threshold. When the method is used for equivalent settings, it is to be expected that the observer will choose each setting within the area of uncertainty. Consequently, the just noticeable difference (j.n.d.) based on the variability of matches will be expected to/

to be less that that obtained by the method of limits. The two methods are, therefore, not directly comparable.

Method of Constant Stimuli

Determinations of the threshold using this method are obtained by choosing a graded series of stimuli in the neighbourhood of the threshold, and presenting these in a random order to the observer. On each stimulus presentation the subject must report either "Same" or "Different" in measurements of the differential threshold, or "Present or "Absent" for measurements of the absolute threshold. It is customary to choose not less than seven equally spaced stimulus values which fall in the region of uncertainty between, for example, 0% yes and 100% yes·responses. Each stimulus value is presented on a number of occasions. The percentage of positive responses is plotted against stimulus values and the stimulus value corresponding to 50% positive response is chosen as the threshold value. The randomness of the stimulus presentation, prevents the subject developing expectancies concerning the responses he will make.

IIb) A Comparison of Methods

Early psychophysicists had great faith in the method of average error or adjustment, and it is still used in many research establishments. Subjects often feel /

feel happier when they can exercise control over the stimulus change being made. There is a certain sense in which a subjective "accuracy" of the measurement has been increased. However, it is precisely at this point that a problem arises. The settings of a subject represent a compromise between what he sees and what he knows about the adjustment of the stimulus. In other words, there is likely to be a large non-sensory element included in the measurement, because it depends upon the subject's knowledge of the adjustment he is making. Here lies the criterion upon which all measurements of visual sensitivity should be judged. How much does the measurement reflect the sensitivity or discriminative power of the visual system per se, and how much is the measurement contaminated by extraneous or non-sensory variables? The method of adjustment represents a more obvious type of non-sensory interference. The orderliness of stimulus presentation in the method of limits sets up expectations which the ascending and descending trials are meant to counter-balance. Nevertheless, the measurement cannot be entirely free from such non-sensory factors. The method of constant stimuli uses an indirect method of assessing the threshold, as this is calculated after the response probabilities have been obtained. This feature was considered undesirable by the early psychophysicists, but it is seen by contemporary research workers to be an advantage of the method./

method.

BLACKWELL (1952) proposed three criteria for assessing visual thresholds. These were: a.) reliability, b.) inferred validity, and c.) sensory determinancy. Reliability is measured by the extent to which repeated measurements, made under presumably identical conditions, vary among themselves. Inferred validity is measured by the extent to which variables which are considered irrelevant to the visual functions of interest, influence threshold data. Sensory determinancy is measured by the smallness (variance) of the threshold data. Blackwell studied the subject's response which is used to indicate discrimination,and the effect of the number, spacing, and order of light intensities on threshold measurement. Subjective attitudes were also investigated, together with the feedback effect of knowledge about correctness of response. His conclusions were summarised as follows "... threshold measurements made by psychophysical methods exhibit unreliability from session to session, and can be influenced by a number of variables which will be generally considered to be irrelevant to visual functions. Variables such as order and spacing of target luminances, suggestion that sensitivity will be increased, and pay incentive, have been shown to influence threshold data. We are forced to conclude that we cannot expect threshold data to yield entirely reliable and valid indices of visual function. Differences/

Differences in the value of the threshold will usually reach 10 to 20%; they will sometimes reach 50 to 75%. These differences are sufficiently large to be important to contemporary visual theory. The differences among threshold data obtained with different procedures are apparently not constant but may depend upon stimulus conditions, such as target size and background luminance. The extent of such dependence may be as large as the differences among threshold data obtained under one stimulus condition." These statements appear to undermine the efficacy of visual threshold data. They certainly give cause for concern in any study which purports to assess visual sensitivity.

Blackwell's recommendations for procedures exhibiting maximum reliability and validity are:-

a. forced choice procedure (see page 24) rather than phenomenal report of "Yes" and "No,

b. forced choice to involve temporal intervals rather than spatial locations,

c. target luminances to be grouped into blocks of the same magnitude rather than to be randomised,

d. as few target luminances to be used in psychophysical series as practicable,

e. subjects to be taught cues for discrimination by notifying them of the correctness of their responses, and/

and/

f. subjects to be given reasonably extensive experience in threshold measurement.

It is clear that while some of the recommendations might be included in a clinical test situation some of the others are quite impracticable. For instance, points e. and f. are impossible to implement because sufficient time is not available. Problems of this nature are reserved for Section IId. Nevertheless, Blackwell's experiments represent a landmark in studies of visual psychophysics. They are probably the most comprehensive attempt to examine the variables underlying visual threshold measurement, if only for the many thousands of results which were collected towards this end.

Two further studies, RIGGS, CORNSWEET, LEWIS (1957), KELSEY, SCHWARTZ (1959), examined the reliability of the method of limits and the method of constant stimuli in absolute threshold measurement. The general conclusion in both studies was that the method of constant stimuli was the more reliable of the two. A more recent study of the adequacy of different methods was carried out by SIEGAL (1961) in the measurement of difference thresholds. Adequacy was assessed against the three criteria proposed by Blackwell mentioned previously. Siegal criticises the method of adjustment on the grounds of a. confusion of motor with perceptual errors due to kinesthetic cues, and b. uncontrolled time of observation in which/

which adaptation effects will influence observer sensitivity. Using the statistical design of an Analysis of Variance between the methods, Siegal found that the method of adjustment led to more variability between sessions than either of the other two methods. He concludes "It seems abundantly clear that the method of adjustment is not the most satisfactory one for determining sensitivity to differences in colour." In the method of limits where the observer's task is to maintain a constant criterion for response throughout the series, Siegal comments, "It is unlikely that any but the most skilled observers are able to carry out this task to the extent demanded by the method". The method of constant stimuli produced the least variability from session to session and appeared the most appropriate method. Each observation led to a judgement which was independent of the others, and randomness of presentation prevented errors of anticipation or habituation. It should be noted that in this study, where each method was presented in its most favourable light. In other words many readings were taken in each threshold determination, so that any error would be at a minimum. Again from a clinical viewpoint is is generally impracticable to devote a similar amount of time in collecting one item of data. For instance, one of the major criticisms of the method of constant stimuli has been its length. However, Siegal found that in order to have the method/

method of limits comparable in accuracy to the method of constant stimuli it would be necessary to have the former far longer.

In all "classical" attempts to determine the threshold, it is clearly assumed that there is a threshold or boundary point there to be determined. Although this boundary changes from moment to moment, the statistical techniques enable us to arbitrarily define the threshold within this variability. There are, therefore, two ways in which the notion of the threshold is used in sensory psychology. In one sense, the statistics give an operational definition of a threshold. In a second sense, the threshold becomes a property of a sensory system so that s transmission barrier is postulated, before afferent impulses reach a decision centre. An anology is made with the all-or-none action in single neurones. At any moment in time, the barrier is either reached or not reached, implying that we detect a light or do not detect it. The variability in the threshold is supposedly due to an instability in the triggering mechanism of the sensory system. This instability results from such factors as stimulus variation (quantal effects), variation in the effect on the receptors, and variations in the threshold magnitude. Because of this, a given stimulus is more "detectable" on some trials than on others, so that observers are more confident about some of their/

their responses than about others.

Research workers have attempted to solve this problem by training their observers to maintain a constant criterion throughout an experiment for "Yes" responses. This"solution" reduces the variability in threshold value but introduces a further non-sensory component in the measurement because the numerical value of the threshold must be interpreted in terms of the criterion used by an observer. The classical methodology does not provide a measure of the observer's response criterion which is independent of the threshold value. This is of fundamental importance to a study of inter or intra individual comparisons of visual discrimination. When test scores which represent discriminative ability are compared, do differences represent changes in response criteria, or genuine visual differences? If one assumes a constant criterion, then any individual differences are due to visual differences; on the other hand if one assumes that sensitivity is constant, then any differences are due to changes in the response criterion. LICKLIDER (1959) states "More and more workers in the field are growing dissatisfied with classical psychophysical techniques, particularly with the methods that ask the observer to report "present" or "absent" when he already knows "present". It is widely felt that the "thresholds" yielded by these procedures are on such an insecure/

insecure semantic basis that they cannot serve as good building blocks for a quantitative science". Although this article refers to auditory thresholds, the difficulties in the threshold concept for vision are paralleled in studies of any sensory modality.

During the 1950's, methods were evolved which provided an independent assessment of both response criterion, and sensory discrimination. By use of these methods, doubt has been cast on the assumptions underlying a sensory threshold. An alternative view of sensory excitation is proposed consisting of a continuous gradation of activity which is artificially dichotomised when an observer is restricted to two response categories. The experiments resulting from the new methodology fall under the general heading of "Signal detection".

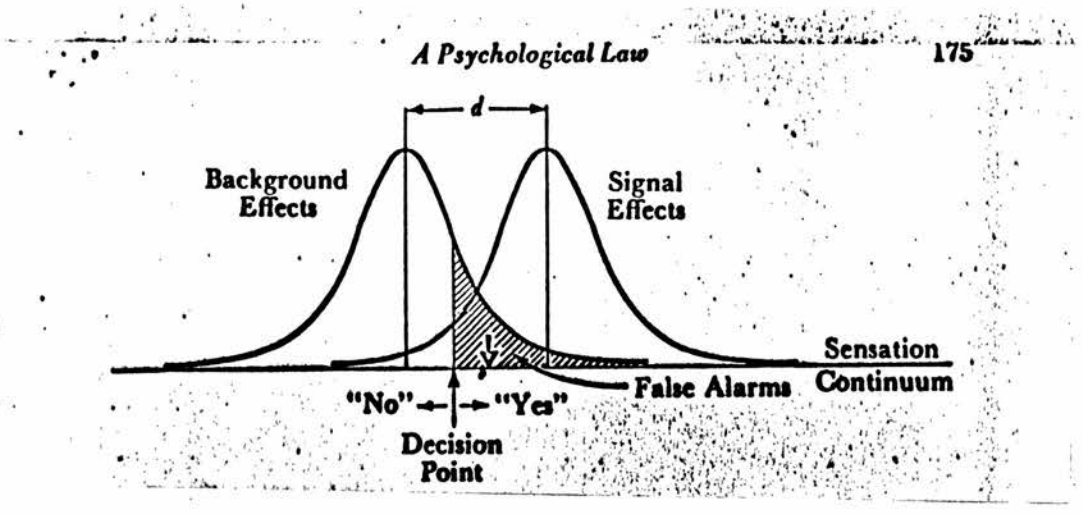
IIc) Signal Detection

Experiments in signal detection usually have as their base, a wider concept of human behaviour than that employed in classical experiments. Experiments do not simply produce information about a particular sensory mechanism, but monitor the behaviour of the whole human being in the test situation as a decision maker. By so doing, a purer measure of sensory discrimination is achieved. The detection theory is in two main parts; one developed from statistical decision theory and the testing of hypotheses, the other introducing the concept of an/

an "ideal observer" who maximises the information presented to him in the environment, PETERSON, BIRDSALL, FOX (1954), TANNER and SWETS (1954).

The main difference between signal detection theory and "threshold theories" hinges on the role assigned to "false alarms". These are positive reports of a stimulus when none is presented to the observer. Under classical theories, the absolute threshold can only be reached on trials on which a stimulus is present. On trials when no stimulus is present, spontaneous neural activity very seldom, if ever, exceeds the threshold. False positives are, therefore, due to guessing on the part of the observer. A good observer trained to maintain a constant criterion for response is a non-guessing observer. In detection theory every observational interval is seen to contain random interference or noise. Sensory excitation is assumed to be continually varying due to noise, and it varies in the absence as well as in the presence of a signal. It also varies on two presentations of what is nominally the same signal. Noise can be produced by the environment, the experimenter's equipment, or by the sensory system itself. In the experimental design, observational intervals which contain both a signal (light stimulus) and noise, and noise alone are included. It is the observer's task to decide whether in a given interval, he prefers the decision that the/

Figure 1.


A Psychological Law
175
d
Background Effects
Signal Effects
Sensation Continuum
False Alarms
"No"
"Yes"
Decision Point

the interval contained a signal, to the decision that the interval contained only noise. Only by including trials on which no signal is presented is it possible to isolate the effects of response criteria from visual sensitivity. The introduction of this new type of trial, illustrates the main experimental difference between classical and modern psychophysical methods. (It should be mentioned that early experimenters occasionally made use of this type of trial but only as a means of checking if the observer was guessing, or in other words was unreliable). A further assumption in detection theory is the introduction of the concept of the likelihood ratio, which determines the response criterion. As the sensory excitation is a continuous variable, the observer's report depends upon the establishment of a cut-off point, i.e. likelihood ratio, along this continuum. Two overlapping Gaussian curves represent the noise, and signal plus noise distributions (Fig.1). The location of the decision point depends upon observer expectation (e.g."a priori"signal probability) and the outcome of the decision in terms of relevant goals before the observer. Several detection goals have been defined and their influence on the criterion assessed, (SWETS, TANNER and BIRDSALL, 1961). An observer's decision is based, therefore, not only on the sensory information he receives, but also upon his motivation and expectations./

expectations.

The simplest application of the new method can be seen in the single interval experiment for absolute detection measurements. In any series of trials, two types of trial are defined. These are, (1) signal plus noise trials (S+N) and (2) noise trials (N). The observer reports after each trial either "Present" or "Absent" depending upon which decision he prefers. The number of (S+N) and (N) trials in a series is determined by the experimenter, who then randomises the presentation for that series. The data falls into four categories usually written in a 2x2 matrix:-

(1) (S+N) trials on which response "Present occurred;

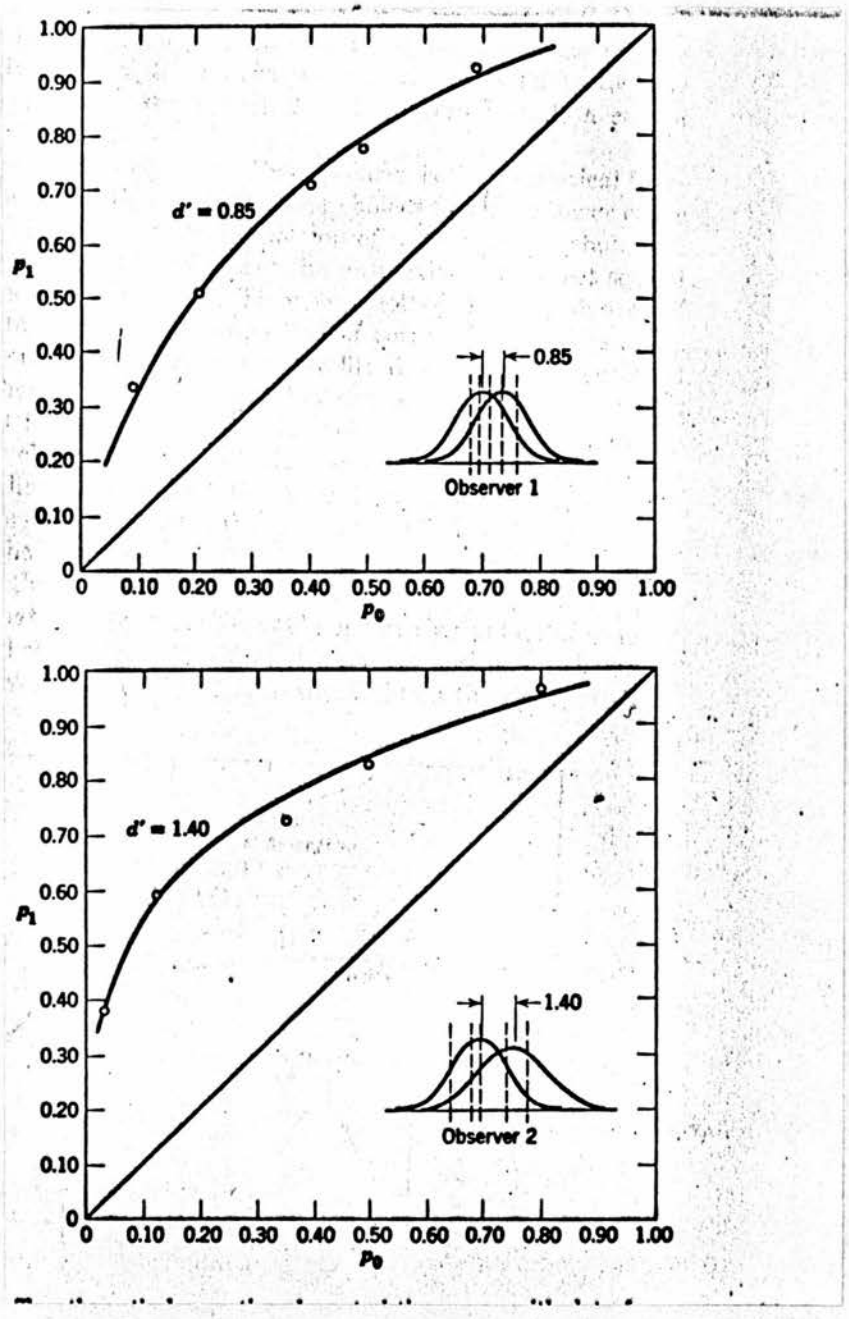
(2) (S+N) trials on which response "Absent" occurred;

(3) (N) trials on which response "Present" occurred;

(4) (N) trials on which response "Absent" occurred.

The two cells of particular interest are numbers (1) and (3), from which the proportion of correct detections i.e. "hits" $\frac{(1)}{(1) + (2)}$ and proportion of false alarms $\frac{(3)}{(3) + (4)}$ can be determined. If according to classical theory, false alarms are due to guessing, it is necessary to have "a mechanism which triggers when seeing occurs, and which becomes incapable/

Figure 2.


d' = 0.85
0.85
Observer 1
d' = 1.40
1.40
Observer 2
P_1
P_0
0 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00

incapable of discriminating between quantities of neural activity when seeing does not occur". (TANNER, SWETS, 1954). It follows from this assumption that a guess would be independent of signal intensity.

A set of 2x2 matrices can be generated by varying the signal intensity or by holding the signal intensity constant and changing the goals or a priori expectation of signal probability. For each matrix, a value of the probability of "hits" and "probability of false alarms" can be calculated which, when plotted as in Fig.2, trace out the receiver operating characteristic (ROC curve). Each curve represents the change in detection resulting from a change in response criterion at a fixed value of signal intensity. As the signal increases in intensity, so the difference between the mean of the (S+N) distribution and (N) distribution (i.e. d') becomes greater and the curve moves further from the diagonal line towards the top left hand point of the diagram. Each curve represents the sensitivity of the observer to a particular signal. Each point on a curve is calculated from one 2x2 matrix and the slope of the curve at that point reflects the criterion used by the observer in generating the matrix. The important point to be emphasised from such a curve, is that the correct detection rate and the false alarm rate appear to be correlated and to vary together (TANNER, SWETS, 1954).

This conclusion is strengthened by data from a/

a forced choice experiment, and a rating scale experiment, conducted by SWETS, TANNER and BIRDSALL (1961). The temporal forced choice experiment has on each trial a set of observational intervals. The subject has to report which interval contains the signal. The rating scale experiment is similar in that in any interval a signal is presented or not presented. The observer's task is to give a value to each interval, which represents the likelihood of that interval containing the signal. Data from both types of experiment support the assumption that sensory excitation is a continuous variable. BARLOW, (1956), showed that by allowing an observer the categories "Possible" as well as "Seen" and "Not Seen", the resultant false positive rate increased only slightly when "Possibles" were added to "Seens". The correct detection rate, however, increased greatly. If there was no spontaneous activity, the "Possibles" would be guesses which would be given most often on catch trials where "the opportunity to guess is greatest". Spontaneous activity must, therefore, be present, and must exceed threshold value at least some of the time. The concept of an ideal observer is introduced to specify the ideal detection performance. This is the decision which makes best use of the available information, given the limits on detection imposed by the environment.

At the beginning of this section, it was pointed out that two assumptions underly many classical/

classical experiments of threshold measurement. Firstly, there is the implication of a barrier to be crossed for "Seeing" to take place; secondly, this barrier is only crossed when a stimulus is present, and hence false positives are due to guessing. Both assumptions are independent and the invalidation of one does not necessarily invalidate the other. A distinction must now be made between high threshold theories i.e. theories which contain both assumptions, and low threshold theories, which maintain that a threshold exists, but do not require the further assumption that spontaneous activity seldom, if ever, crosses the threshold. High threshold theories (e.g. BLACKWELL, 1953) have certainly been questioned by the signal detection approach, but the situation is far less clear when the low threshold theories are considered (LUCE, 1963). Of the latter, two state threshold theories, as well as theories with several fixed thresholds have been proposed (LARKIN and NORMAN 1964: NORMAN, 1962). However, in a study of absolute visual detection (NACHMIAS and STEINMAN, 1963) in which the rating scale method was used, the data supported the statistical decision theory, (no fixed threshold) rather than a two state low threshold theory. As the number of proposed thresholds increases, it becomes increasingly difficult to distinguish on empirical grounds, between such a theory and the/

the statistical decision theory, NORMAN (1962). Quantal threshold theories (STEVENS, 1961a, 1961b) are seen by SWETS (1961) to be not directly comparable with other theories, because in the experimental method an attempt is made to eliminate noise, whereas in some of the other theories, noise is deliberately added Furthermore, elite observers are necessary who "know" that signals of the same intensity will be presented on a set of trials. "This procedure provides an unfortunate protection for the theory; if the observer is likely to make noise determined "Yes" responses, the fact will not be disclosed by the experiment". Similarly, CORSO (1956) questions whether experiments supporting a quantal threshold, do in fact do so. It appears that while the high threshold theory may be rejected on the evidence above, there still remain several alternative theories for consideration, which are not rejected by empirical evidence. A comprehensive review of the threshold concept is given by CORSO (1967).

IId) Practical Considerations

Following the advent of signal detection theory several authors have reported practical problems in the application of such a theory to visual detection experiments. Some problems arose from attempts to measure both the visual sensitivity and the response criterion. It has been previously mentioned that the false alarm rate/

rate could be changed by either altering the observer's expectation of the likelihood of a signal, or by adjusting the observer's goal in terms of rewards or punishment associated with each set of trials. In either case the effect is to alter the criterion for a response. The limits of the receiver operating characteristic for both the probability of hits and the probability of false alarms is 0 and 1. In practice it has been found difficult to manipulate the experimental parameters to give a high false alarm rate. BURGHARDT and HILLMAN (1961), demonstrated that the overall percentage of false alarms is about 0.7% for trained observers and 2% for less experienced observers. BARLOW (1956), showed that by including the response "Possible", the false alarm rate increased only slightly by 1%. BITTINI and FUJIWARA (1964), found that an observer's knowledge of the signal probability was not sufficient to induce the observer to change his criterion. In addition correlations between the absolute threshold and false alarm rate were small and insignificant (BITTINI, GLORIA, 1968). It appears that it is extremely difficult to change the observer's criterion sufficiently to trace out the receiver operator characteristic. In the consideration of experiments which are directed primarily to a measure of visual sensitivity, questions of motivation and their effect upon response criterion are of secondary importance. The above studies/

studies indicate that measurement of the response criterion as a means of control is extremely difficult. In addition information is obtained which is unnecessary to studies of visual function. A further objection, which is particularly relevant to clinical testing is the amount of time necessary for such a signal detection paradign. EGAN and CLARKE (1966), recommend around 200 observation intervals for the establishment of one 2x2 matrix. Certainly, SWETS (1961), insists that a large number of catch trials are necessary to monitor the observer. At the very least 3 matrices are required for an ROC curve and consequently the experimental time required would be quite prohibitive. It is also worth remembering that at the end of this time, sensitivity at only one retinal position will have been determined. Such methods are clearly ruled out of any clinical test procedure and are only applicable in research situations.

An alternative approach is not to measure the response criterion but instead to hold it constant so that variations in experimental results are solely attributable to variations in observer sensitivity. This can be attempted by means of the forced choice procedure. It is recommended by EGAN and CLARKE (1966) if the problem involves detectability of a signal under various stimulus conditions, and by SWETS (1961), if the study has an emphasis on sensory rather than on/

on motivational processes. For the temporal forced choice procedure, two observation intervals can be used, one of which always contains the signal. Precisely which interval in any pair contains the signal, is decided on a random basis over the number of trials. Estimates of sensitivity derived from forced choice experiments are comparable with those from the single interval experiment. This applies when up to as many as 8 intervals are used in the forced choice method (SWETS, 1959). (This finding is to be contrasted with the variability between methods in measures of the "threshold" BLACKWELL (1952), SIEGAL (1961)). As the forced choice procedure does not require an estimation of the response criterion, the only problem is to eliminate any observer bias towards one of the intervals. Both Egan, Clarke and Swets suggest that the observer does not in general show a strong bias towards one of the intervals and that even if he does, this can easily and quickly be corrected. Consequently, the observer chooses the interval which is most likely to contain a signal independent of any response criterion, and the percentage of correct decisions can be used as a measure of observer performance.

The rating scale procedure must also be mentioned in this context as it is a widely used procedure with much to recommend it as an experimental method. By asking the subject to grade his responses into, say,/

say, five categories ranging from a high degree of certainty that a signal trial occurred, to a high degree of certainty that a noise trial occurred, a receiver operator characteristic curve is obtained with the six categories representing response criterion points along the curve. Two advantages of the method are, firstly, that additional information about response criteria is obtained, and secondly, that the trial length is less than that of the forced choice procedure. It has been shown (GREEN and SWETS, 1966) that the area under the ROC curve is equivalent to the percentage of correct decisions in a forced choice experiment. This area varies from 0.5 (chance performance) to 1 (perfect performance) (see Fig. 2). Some recent applications of this method in the detection of luminous increments are made by NACHMIAS and KOCHNER (1970); BAGRASH, KERR, THOMAS (1971); THOMAS, KERR (1971). Whether unsophisticated observers or patients attending eye clinics could be persuaded to use a rating scale, remains rather doubtful. Consequently, of the available methods the forced choice procedure appears to be the best practical compromise. (Most of the experiments reported here have dealt with either absolute detection or the detection of luminous increments. An extension of signal detection theory to the matching situation has been provided by SORKIN (1962). Using three variations of the matching situation, Sorkin/

Sorkin demonstrated close agreement between prediction and matching performance across different tasks.)

A deliberate attempt has been made in this section to examine the methodology which underlies most experiments on visual function. It is the writer's opinion that such an examination is essential and must be carried out prior to any data analysis. Many experiments take no account of this. Others implicitly assume a classical model so that GUTH (1971), can write "In several recent articles, papers and books (IKEDA, VETSUKI and STILES, 1970; KRAUSKOPF, 1970; PIRENNE, 1971), psychophysical data have been interpreted using the probability summation model. This (model) is only appropriate within a very restricted and probably incorrect classical theory of visual threshold. ... the continued use of the probability summation approach by visual scientists suggests that it is timely to review the issue."

What conclusions can be drawn from this examination? Firstly, if at all possible, the signal detection methodology should be used preferably in the forced choice or the rating scale paradigm. It is the only method which enables observer sensitivity per se to be isolated from psychological variables which determine the response criterion. The rating scale method will enable an ROC curve to be determined and give two independent assessments of detection and criterion. The/

The forced choice method can be assumed to be independent of criterion effects and results in a measure of detection only. These powerful methods are ideal in the study of small differences in the capacity of the visual system to detect a light stimulus and should facilitate research procedures. In the clinical field, they would also aid the assessment of early changes in sensitivity so that small test score differences would become meaningful in sensitivity terms. If the research or clinical situation does not warrant such finesse so that the measurement can be at a relatively cruder level, then of the classical methods that of constant stimuli is by far the best. The method of limits is recommended after this.

It is important to recognise the level of measurement in absolute terms which is under discussion, so that the different methods will be seen in perspective and contrasted with the usual way of collecting data in visual function experiments. As far as is known, there is no clinical test of visual function at present in use which uses anything but a variation on the method of limits. The "variations" are, in fact, departures from a strict application of the method. These departures are frequently of the following types:- a.) lack of standardisation of test procedure, b.) lack of control over stimulus variables and experimental situations, c.) number of trials restricted, and/

and d.) one way determinations of the threshold. (In many cases the threshold is approached from only one direction e.g. either from supra-liminal to sub-liminal as in acuity tests, or vice versa as in both static and kinetic perimetry. As to the number of trials, it is generally assumed that the error in measurement varies as the square root on the number of measurements taken). Any departure from a strict application of the method from whatever source, will add to the error in the measurement. Clearly, some tests of a very crude nature can yield useful clinical information and time may not permit a more detailed examination. Nevertheless even in this situation an awareness of relevant factors in the test situation can make the testing more meaningful.

It has been the aim of this section to examine implications in visual function testing and to point to powerful methods available for anyone who wishes to use them. It is up to the tester to strike a balance between the amount of information collected, the time available in which to collect it, and the accuracy he desires from his data. Further discussion on the appropriateness of the methods of testing for each of the selected tests is given under the "Development of Tests" section.

III NORMAL VISION

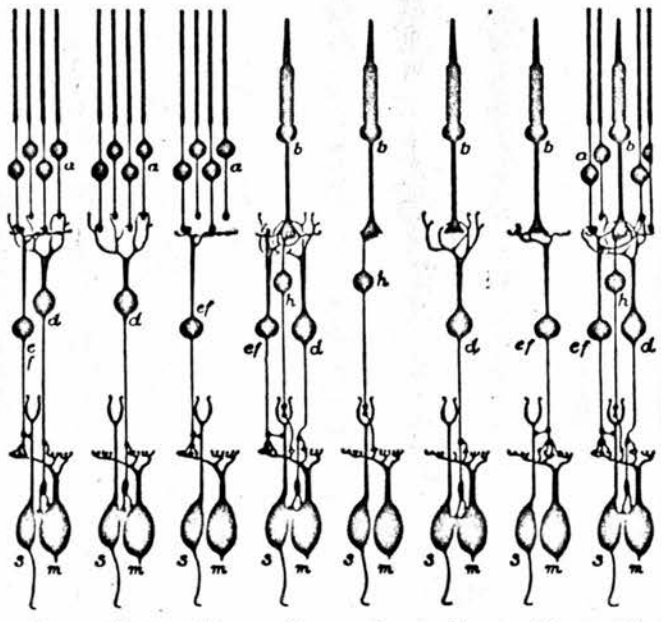
The functions of normal vision provide the setting for all subsequent comparisons in which the visual system has been affected. Many of the assumptions and developments of subsequent chapters, rest on the framework in which two basic types of retinal activity can be distinguished. These two mechanisms are referred to as the photopic and scotopic systems. It is important, therefore, firstly to consider some of the evidence on which these mechanisms are based, and secondly to consider evidence for the further subdivision of the photopic system. Following this, electrophysiological evidence of normal visual processes is presented.

Finally, before a discussion of psychophysical results in normal vision, the possibilities of linking physiological with psychophysical evidence are considered. The chapter is concluded with a discussion of the "Standard Observer" - a mathematical concept in which a reference system for the perception of stimuli is completely defined. This forms a basis for an analysis of visual function tests and colour vision anomalies.

IIIa) Evidence for Retinal Duality

1. Anatomical

The founder of the histology of the retina is/



A = rod system
B = reduced rod system with mop bipolar
C = reduced rod system with brush or flat top bipolar
D = complete cone system
E = reduced cone system with midget bipolar
F = reduced cone system with mop bipolar
G = reduced cone system with brush or flat top bipolar
H = mixed complete rod and cone system

a = rod
b = cone
d = mop bipolar
e = brush bipolar
f = flat top bipolar
h = midget bipolar
m = any diffuse ganglion
s = midget ganglion

FIGURE 3 —Grouping of neurons of the primate retina into functional systems by Polyak

is TREVIRANUS, who in 1835 discovered visual cells which act as receptors. In 1846, BOUMAN discovered six retinal layers, and in 1850 CORTI traced the path of the nerve fibres from the receptors to the optic nerve. The photo-sensitive function of the retina was experimentally demonstrated by MULLER (1857), in in the movement of entoptic shadows produced by blood vessels in the retina. The first description of two types of receptor cells, cones and rods, was made in 1866 by SCHULTZE. Schultze found that certain vertebrates with nocturnal habits (deep-sea fish, owls, bats) possessed only rods, whilst some diurnal animals (e.g. birds, lizards) had only cones. Later evidence, however, (e.g. VERRIER, 1945), suggests that there are several exceptions to this type of argument from comparative anatomy. For a further description of the historical developments and for all references see LE GRAND (1968) page 357.

The most frequently quoted reference in retinal anatomy is that of POLYAK (1941, 1957). The different types of cells in the retina and their synaptical relationships are shown in Fig. 3; this diagram is taken from SHEPHERD (1968), p. 69, who brings attention to Group D. It is generally assumed that there is a 1-1 correspondence between cones, bipolars and ganglion cells. But clearly Polyak is suggesting that each cone is connected to three or possibly four bipolars, so that it is possible that excitation from a single cone can/

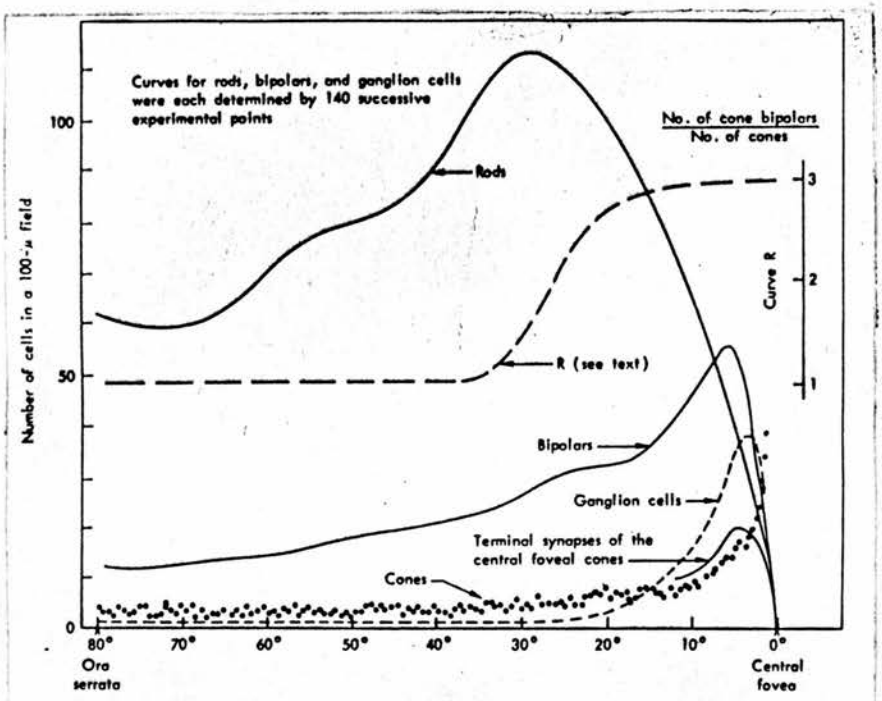


FIGURE 4 —Distribution of neurons in a 2-μ-thick dorsoventral cut through the human retina, extending from the central fovea to the ora serrata by Vilter

can affect a bipolar in three different ways. Polyak demonstrates clear anatomical distinction between two types of receptor - rods and cones - wherever they are found in the retina. Additional evidence comes from VERRIER (1945) who showed that these cells are extreme forms of a single type, intermediate forms being found in certain animals. However, in more recent times, evidence has been accumulated which in general supports the notion of two receptor types from a functional viewpoint, but tends to blur the anatomical distinctions between two types of receptor WEALE (1961), DOTT (1962), PEDLER (1965). There is still doubt regarding the extent of the rod-free area. Estimates vary between 50 and 90 min. in angular diameter, OSTERBERG (1935), POLYAK (1941). Functionally the extent of the rod-free area is 1 - 1.3° as no effect of rod function has been present in studies with fields of this size (DUKE-ELDER 1968).

The distribution of neurones in the retina is shown in Fig. 4, after VILTER (1949). The variation in the number of rods and cones is shown from the fovea out to 80° in the peripheral retina. Additional information concerning the neuronal interconnections is also shown in the diagram. (Although this is not evidence for an anatomical distinction between receptor types, it is included here as it suggests an interesting relationship between structure and function). In the/

the outer periphery the cone and ganglion distributions are fairly constant with a ratio of 3:1 in a 100 mu field from 80°- 35°. In this area the increase in rod population is matched by an increase in the number of bipolars resulting in a ratio of rods to bipolars of 5:1. Within 35° of the fovea all the ratios change. However, if the rod: rod bipolar ratio is assumed to remain constant, the cone: cone bipolar relationship is shown by curve R. This curve shows a 1:1 relationship at 35° excentricity; a 2:1 relationship at 28° excentricity; and 3:1 relationship at 15° excentricity. The implications of the data from Polyak and Vilter may be related to the colour zones of the visual field. In regions where the ratio is 3:1, colour vision is trichromatic; in regions where it is 2:1, dichromatic; and in regions where it is 1:1, achromatic (after SHEPHERD, 1968). It should be emphasised that this is a correlation between structure and function given that certain assumptions (namely that the rod: rod bipolar ratio remains constant) are valid. Very recent measurements by DOWLING and WERBLIN (1969) using electron microscopy are likely to clarify such assumptions and to open up new possibilities for the understanding of the neural interconnections at the retinal level.

In general, the anatomical distinctions between rods and cones as revealed by microscopic examination/

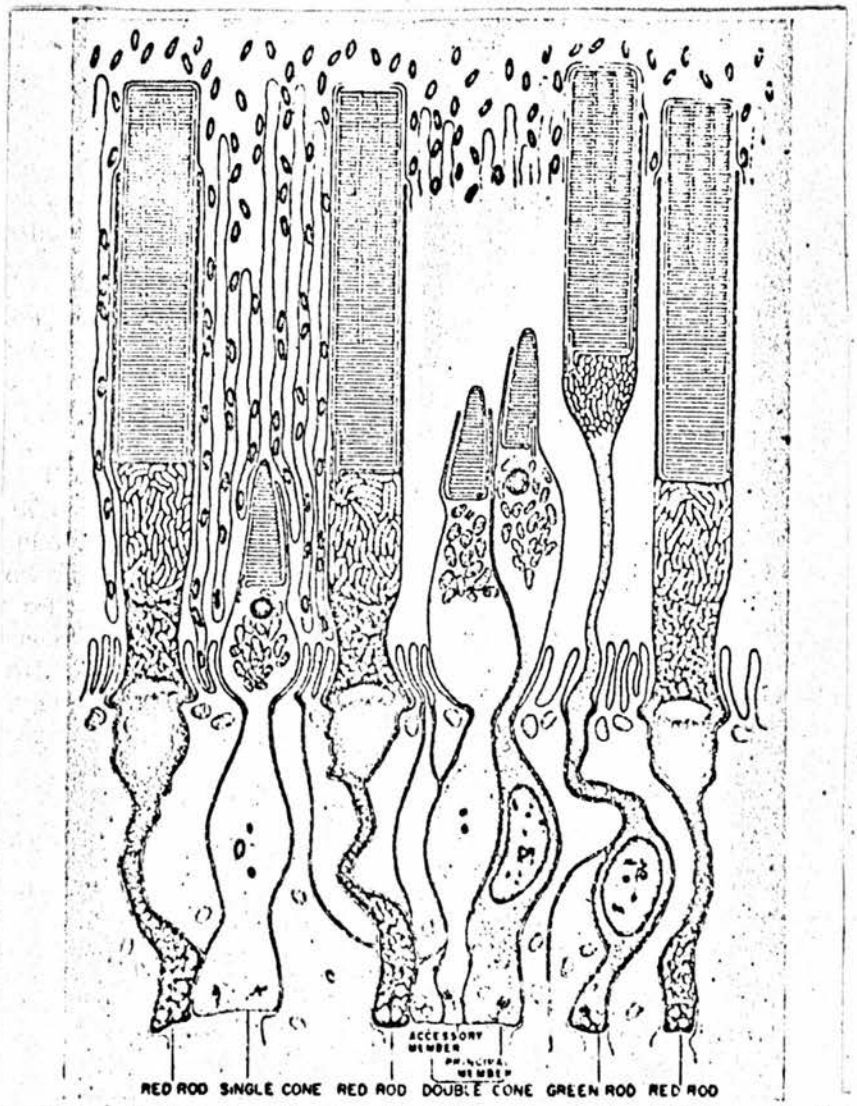


Fig. 5. Schematic drawing showing the different receptor cell types in the frog retina. (*Nilsson* 1964.)

examination are descriptive of the outer limb of these receptors. A comparison of the structure of rod and cone outer segments has revealed that rods contain separate transverse laminal discs, whereas the cone laminations are continuous with the receptor outer wall, (Fig. 5 and 6, from CRAWFORD and IKEDA, 1971). In areas where the gross differences in receptor outer limbs do not exist, these structural differences remain. Furthermore, YOUNG (1969), has shown that the rod discs are being continuously formed, and that they move up the receptor until they are finally broken down by the pigment epithelium. On the other hand the cone outer segments remain permanent. In addition to the differences of the outer limb, the inner limbs of the cones tend to be more bulbous than those of the rods, and the cone pedicles with which the receptor is linked to the inner nuclear layer are spatially more diffuse than corresponding rod sphericles,(RUDDOCK 1971). Despite these apparently well-founded differences, doubt still remains about a system of classification based on purely anatomical criteria for distinctions between rods and cones (PEDLER, 1969).

2. Physiological

It is much easier to point to physiological differences between the two types of receptor. Of/

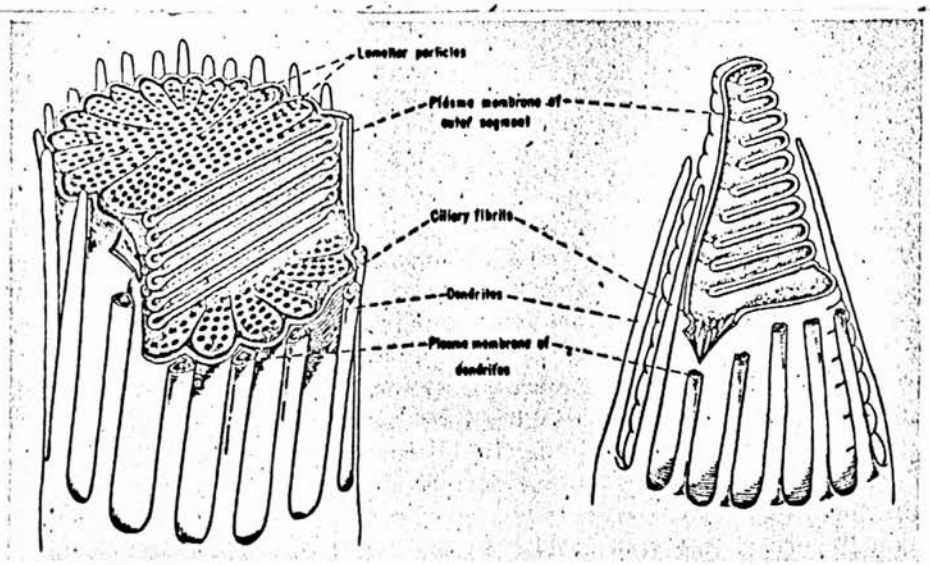


Fig. 6. Schematic drawings to show fine detail of the structure of rod (left) and cone (right) outer limbs (Necturus). (*Wald et al.* 1963.)

Of these, differences in cell chemistry are presented first, followed by functional differences.

(i) Pigment Differences

The possibility of rods and cones having similar photochemical systems is unlikely. Evidence on this type of rod/cone differentiation comes from the studies of NOELL (1958). The intravenous administration of iodoacetate to monkeys showed the receptor cell population to be affected whilst the pigment epithelium, bipolar, and ganglions remained intact. However, in the photoreceptor region itself, a greater proportion of rods than cones were found to be destroyed. The same selective damage occurred under x-ray treatment. The foveal cones appeared normal when almost all the rod cells had been destroyed. This suggests different metabolic organization of rod and cone cells. In onto-genetic studies on rabbits by the same author, the development of rods and cones was quite different. The scotopic part of the ERG showed slow maturation (up to 90 days) whilst the photopic part was well developed by the twelfth day. Noell explains this difference on a chemical basis.

Recent measurements by RUSHTON (1965) have demonstrated differences in the kinetics of the two pigments. By using retinal densitometry Rushton found that the time course of regeneration of rhodopsin in the living eye was almost complete after 40 min. The/

The regeneration follows an exponential curve with a 'half life' of 5 min. Cone pigments also bleach, but follow a regeneration curve with a 'half life' of 1.5 min. (These regeneration rates correspond well with the psychophysical dark adaptation curve, which shows that visual threshold changes follow two similar time courses).

The search for rod and cone pigments has met with mixed success. Attempts to extract pigments from receptors have only been successful for the rods. A comparison of the absorption spectra of rhodopsin (the pigment in rod outer segments) with the human scotopic luminous efficiency curve shows good agreement, CRESCITELLI and DARTNALL (1953); WALD and BROWN (1958). (See below for description of scotopic luminous efficiency). This conclusion is supported by evidence from other sources e.g. extraction techniques to estimate rhodopsin concentration WALD and BROWN (1958); reflection densitometry of the living eye (WEALE, 1962; RUSHTON and CAMPBELL, 1954); and transmission densitometry in single rod elements (BROWN and WALD, 1964).

This general agreement for the rods should be contrasted with the situation for the cones. By use of extraction methods in all cone retinas (WALD, 1937; DARTNALL, 1960) a pigment similar to rhodopsin was extracted and identified as iodopsin. (Wald concluded that the difference between this pigment and rhodopsin/

rhodopsin lay in the protein molecule, with the retinene molecule remaining the same in both pigments). However, attempts to compare the amount of pigment extracted by Dartnall with in vivo bleaching measurements, produced conflicting results. The density of pigment inferred from bleaching experiments was much greater than that obtained by extraction. Both Rushton and Weale have reconciled this discrepancy by assuming that the shape of cones act as wave guides and so enhance the effect of minute amounts of pigment in the receptors. However, at the present time iodopsin remains the only cone pigment to be extracted.

(ii) Functional Differences

The principal functional differences between rods and cones in human vision may be summarised as follows:-

(a) The effect by which certain colours change their apparent brightness in dusk and in daylight was reported by PURKINJE (1825). General acceptance of the fact that there are two distinct types of activity in the retina dates from VON KRIES (1896), and the terms photopic and scotopic were introduced by PARSONS (1915). The scotopic, or rod mediated system is concerned with the detection of light, and is achromatic, and functions in conditions of dark adaptation. The photopic, or cone mediated system, is concerned with form vision and colour vision, and functions in conditions of light adaptation. This functional duality of the retina has/

has been seen by several authors to correspond very well with the histological duality of the retina. The agreement is not likely to be exact, for in any area possessing cones there may well be a few rods which are swamped in response terms by the preponderance of cones.

(b) During the process of dark adaptation the visual threshold changes in a biphasic form, suggesting two different underlying processes. The earlier part of the process is thought to depend on cone function, while the latter part is thought to be due to rod function. The data shows good agreement with the regeneration of cone and rod pigments (RUSHTON, 1965).

(c) The frequency response of rods and cones is quite different. If the retina is illuminated under dark adapted conditions the flicker fusion frequency remains constant at roughtly 15 cycles per sec. This constancy holds over illumination levels up to 10 trolands (HECHT and SHLAER, 1936). Under light adapted conditions however, (when cones are active), the flicker fusion frequency rises to 60 cycles per sec. and is now dependent on luminance level. SHEPHERD (1968) thinks it unlikely that this difference can be attributable to differences in bipolar and ganglionic pathways. He sees the difference as a photochemical one, such that rods fail to respond at high frequencies.

(d) The visual acuity of rods is much lower than that/

that of cones, being maximal for foveal cones. The rods are grouped into functional units which exhibit greater spatial summation than the cones, which are relatively more independent. Although the rod acuity is restricted by these units, the units do enable rod thresholds to be lower than those of the cones. While the condition for rod and cone stimulation is the same (two quanta captured within 0.1 secs.) the rods have the lower threshold due to a greater capture area.

(e) The efficiency of a light in stimulating visual perception depends on its wavelength. The spectral sensitivity of rods peaks at 505 nm., whereas that for cones peaks at 555 nm. Transitions between the two sensitivity curves are seen as either the retinal illumination level is increased, or the information is collected from predominantly rod and cone areas of the retina.

(f) Cone sensitivity depends upon the angle of incident light. They are highly directional in sensitivity, whereas rods are equally sensitive at different angles of incidence. The relationship between cone sensitivity and the angle of stimulation is known as the Stiles-Crawford effect (STILES, CRAWFORD, 1933).

On the basis of evidence from different sources, it appears that rods and cones are different types/

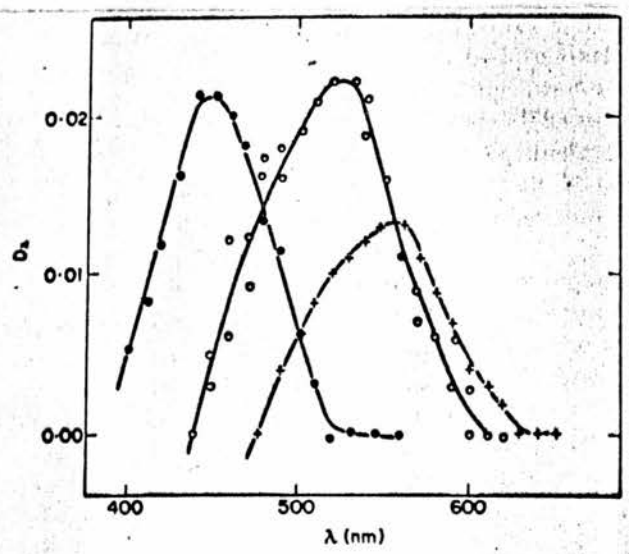
types of receptor. Having established the differences, the mechanism of each type is now examined; the rod system very briefly, as this is mainly a restatement of data already presented; the cone system in detail, as no reference has been made to the subdivisions within the 'cone' category.

Mention has been made of the close agreement between the absorption properties of rhodopsin, the pigment found in the outer limb of rods, and the spectral sensitivity curve of scotopic vision. Rhodopsin has been found in the intact living human eye by fundus reflectometry methods. The technique agrees closely with other methods in determining the absorption spectrum of the pigment (RUSHTON, 1956). Finally, rod pigments from different species all appear to have identical absorption spectra (DARTNALL, 1952). It appears reasonable to conclude that the scotopic mechanism is mediated by a simple receptor mechanism, the rods. Mention has also been made of the lack of agreement between cone pigments and the photopic sensitivity curve. Although only iodopsin has been extracted from cones, evidence is now presented for the further subdivision of cones into different types. Psychophysical data (colour matching experiments and the trivariance of vision) is to be found on page 71 . However, this information is particularly important to the question of cone types, as it requires that the human visual system possesses/

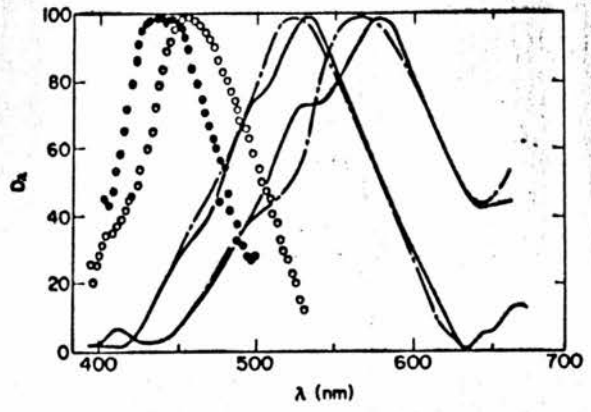
possesses at least three independent systems for the coding of colour, and that the outputs of these systems are maintained fairly separate throughout the visual system. This evidence does not in itself indicate that the different systems are based on photopigment differences. (The effect of receptor geometry has already been mentioned). Nor does it require the existence of three sensitivity systems in the retina. There may be more than three at some point prior to a three channel stage. This depends upon the interconnections at subsequent stages beyond the receptor level. What it has done is to encourage research towards the delineation of at least three receptor types.

IIIb) Cone Types

The existence of different cone pigments has been inferred from spectral absorption data of the human retina. By using fundus reflectometry in rod free areas of the retina, it appears that more than one photopigment is present in human cones, RIPPS and WEALE, (1963); RUSHTON (1958). This technique has not been carried out successfully in a normal eye, and the method has only been used in cases of defective colour vision (See page 95). However, as it is possible that defective colour vision is a reduced form of normal vision, the implications for different photo-/



(*a*)



(*b*)

Figure 7

. (*a*) The spectral absorption spectra of individual human cones as determined by Brown and Wald (1964). (*b*) As above, for six single cones, as determined by Marks, Dobelle and MacNichol (1964)—relative absorption, D_λ, is plotted against wavelength λ.

photopigments in normal vision are clear. Fundus reflectometry does not altogether rule out the possibility of waveguide effects (due to cell geometry) accounting for the spectral absorption of different classes of cones, and yet only one single pigment in the cones being present. However, BRINDLEY and RUSHTON (1959) carried out an experiment in which two sources of monochromatic light entered the eye, one normally, one passing backwards into the retina through the sclera. The transcleral light was found to be essentially the same colour as the normally incident light thus ruling out the possibility of spectral sensitivity being solely dependent on cell geometry. (There is no evidence that cones are symmetrical funnels equally effective when light enters them at 180° to the normal path). These findings are in keeping with the inference that different pigments are the basis for different types of cone. Additional support for the conclusion is given by microspectrophotometry, in which the absorption spectra of individual receptors is measured, (MARKS et al, 1964; BROWN and WALD, 1964). Measurements carried out on excised human and monkey retinae yield three different absorption spectra, (Fig. 7) indicating three classes of cone. (This technique was first used on the cones of goldfish which are larger than primate cones. The three absorption spectra obtained were not due to waveguide effects as the cones/

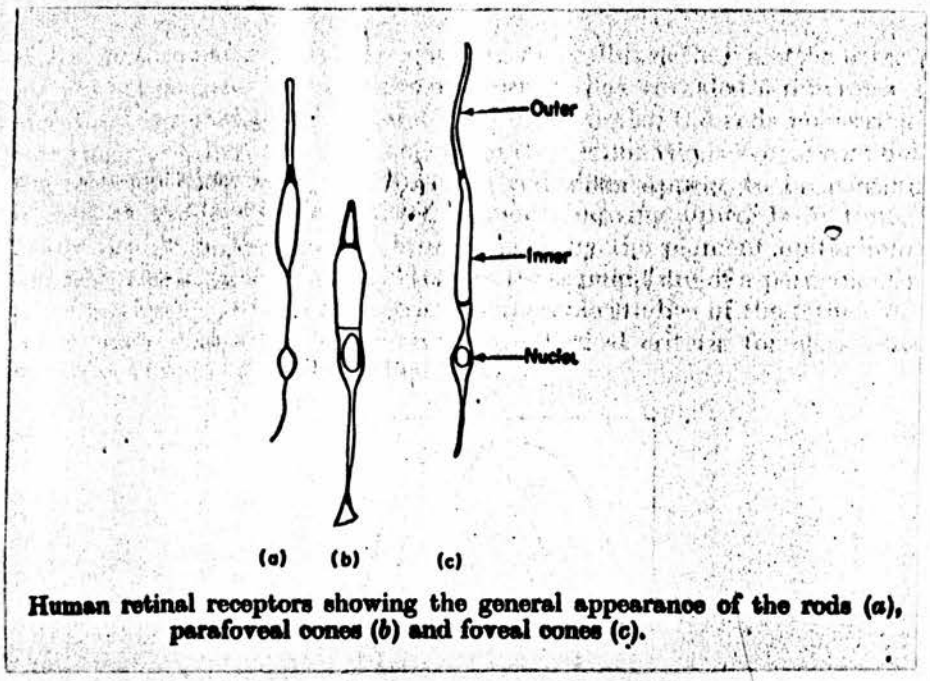


Figure 8

Human retinal receptors showing the general appearance of the rods (*a*), parafoveal cones (*b*) and foveal cones (*c*).

cones were illuminated at right angles to the cone axis).

These findings seem to establish that there are three classes of cone in the human retina, and that photopigment differences are responsible for the major shifts in spectral sensitivity. Waveguide effects may well influence the sensitivity curves, but it seems unlikely that cell geometry is solely responsible for the shift in sensitivity. Furthermore if cell geometry was the major factor, rods which also have a thin outer limb ought to display waveguide effects. Again foveal and parafoveal cones, which have different shapes, display the same effect. An explanation of this may lie in the differences in structure shown in Fig. 8.

The three classes of cone have spectral functions for:-

(1) a blue mechanism peaking between 440 and 450 nm.

(2) a green mechanism peaking between 520 and 540 nm.

(3) a red mechanism peaking between 550 and 580 nm.

(MARKS et al 1964; BROWN and WALD, 1964).

The two pigments which Rushton has identified in defective colour vision (using fundus reflectometry) have peak absorptions around 541 nm. (chlorolabe), and 591 nm. (erythrolabe).

Further implications for the receptor mechanisms will be dealt with in the section on defective colour vision. Particular emphasis has been given to the/

the receptor stage of the visual process, because the principal functional divisions in vision are in terms of the photopic and scotopic mechanisms, followed by a subdivision of cone types. Before dealing with function in purely psychophysical terms, a short account is given on electrophysiological knowledge at different stages in the visual process.

IIIc) Electrophysiology

1. The Retina

Experiments in dark adaptation, colour matching and naming, and the psychophysiology of brightness, suggest the presence of a non-linear transformation of the visual signal at an early stage in the visual process. (CORNSWEET p. 128, 249, 269). In addition to this indirect evidence in human vision, there are direct physiological observations which suggest that this transformation is approximately logarithmic, and operates between the absorption of quanta by the receptors and the generation of nerve impulses.

FUORTES, (1959) examining the eye of the horse-shoe crab, demonstrated that light falling on a receptor produced a chemical mediator which altered the resistance of a cell membrane adjacent to the receptor. The decrease of resistance of the cell membrane produced a change in cell voltage which was related to the frequency of nerve impulses, so that the membrane/

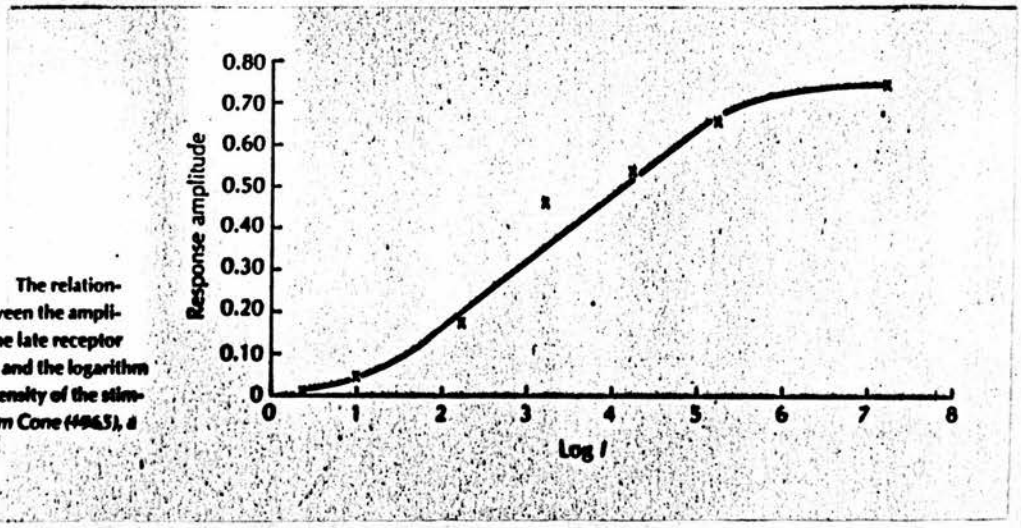


Figure 9 The relationship between the amplitude of the late receptor potential and the logarithm of the intensity of the stimulus. (*From Cone (1963), a wave.*)

membrane resistance and the frequency of impulses were linearly related. As the membrane resistance was proportional to the logarithm of light intensity (RUSHTON, 1961), there was a logarithmic relationship between light intensity and impulse frequency in this primitive eye. BROWN et al (1965) working with monkeys, demonstrated that when an intense flash is delivered to the retina, two receptor responses could be distinguished. One response began almost instantaneously with the onset of the light, while the other followed the first by 1m.sec. The first response, the early receptor potential (e.r.p.), is possibly an indication that a large number of electrical charges have moved due to the onset of light. Molecules which change shape upon light absorption may account for this. The origin of the second response, the late receptor potential (l.r.p.), is not known. However, CONE (1965) has investigated the relationship between light stimulus intensity and response amplitude. The e.r.p. was directly related to the number of pigment molecules which had been isomerised by the light stimulus. Consequently this potential varied linearly with intensity over a wide range of intensity levels. On the other hand the l.r.p. was found to be proportional to the logarithm of light intensity over a wide intensity range of intensities (Fig. 9).

Both the early and the late receptor potentials/

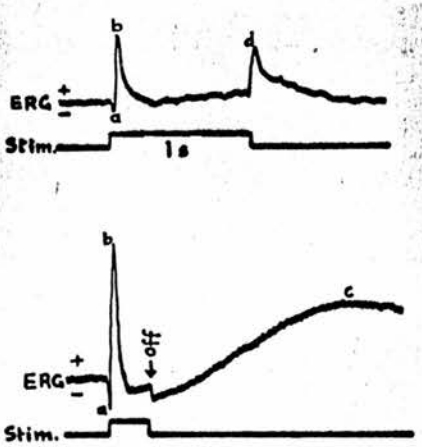
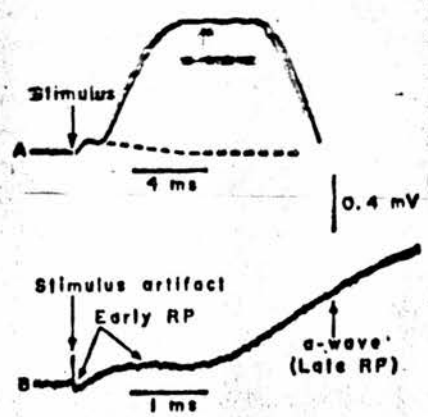


Figure 10 Electroretinograms of cone retina of squirrel (above) and of dark adapted, rod rich retina of cat (below). (*Arden and Tansley* 1955, *Brown* 1968.)



Early receptor potential (ERP) of *cynomolgus* monkey. Note biphasic character of ERP shown in lower trace. (*Brown and Murakami* 1964 a, b.)

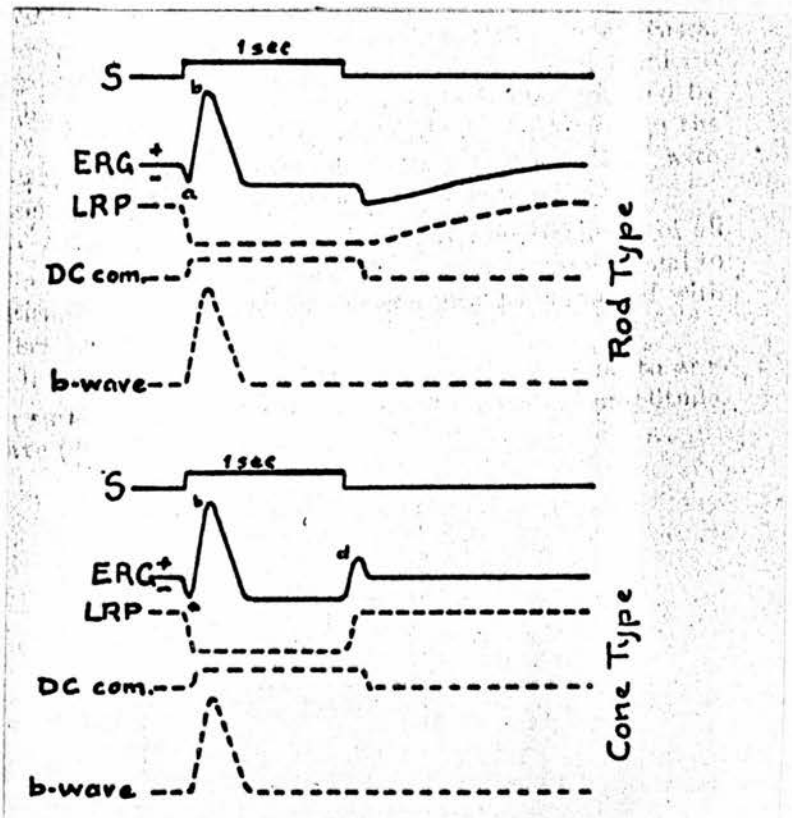


Figure 11 Analysis of rod and cone type electrograms. (*After Brown* 1968.)

potentials are recent additions to the electro-retinogram (E.R.G.), the general features of which were analysed by GRANIT (1947). Fig. 10 shows typical features in a cone retina and a dark adapted rod retina. The e.r.p. precedes the a-wave in this figure, and since its discovery, the a-wave itself has been named the late receptor potential. A recent analysis by BROWN (1968) localised the various components in the following way: (See Fig. 11)

The e.r.p. results from rod and cone outer limbs.

The l.r.p. (a-wave) results from complete photo-receptors.

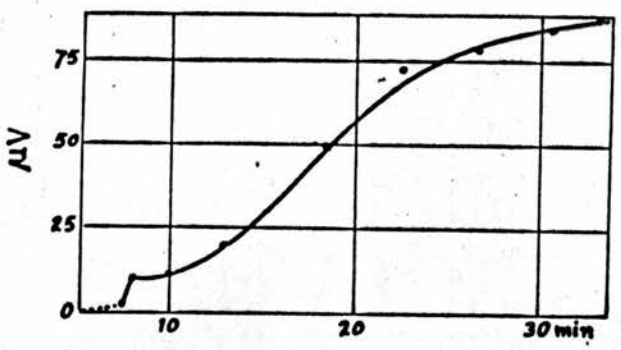
The b-wave results from bipolar cells and inner nuclear layer.

(The oscillatory potential is also from this layer but results from other cells e.g. amacrine).

The c-wave results from the pigment epithelium, but also requires that the receptor cells are functioning.

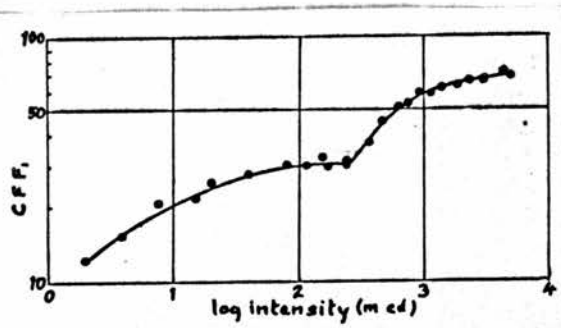
The components of the E.R.G. correlate with certain psychophysical observations. The most prominent in this respect is the amplitude of the b-wave (See Fig. 12 and Fig. 13) in which the b-wave amplitude is followed during dark adaptation (WREDE, 1947). Other correlations of interest are:

(a) The b-wave amplitude is proportional to the logarithm of light intensity over normal/



Variation of amplitude of b-wave (ordinates) with time (abscissae). (*Wrede* 1937.)

Figure 12



. Variation of critical fusion frequency with light intensity as detected in the ERG b-wave of the cat: note the duplex response linked with retinal rods and cones. (*Dodt and Wirth* 1953.)

Figure 13

normal ranges of illumination.

(b) The relation between area and intensity of a stimulus at visual threshold also holds for measurements at constant b-wave amplitude. [Experimental conditions in which Ricco's law is valid (RICCO, 1877).]

(c) The critical fusion frequency as assessed by the b-wave, correlates well with psychophysical measurements. (DODT and WIRTH, 1953)

With regard to (a), physiological evidence has already been given for a logarithmic transformation early in the visual system. In psychophysics, the Weber-Fechner law is a particular instance of this process at work. Most of the tests which are developed in Section V have scales of light intensity in logarithmic units. While this is necessary for the convenient handling of large intensity ranges, it is not simply a matter of expediency. It is because the logarithmic scale has this close connection with visual processing that it becomes a meaningful way of collecting data in visual detection experiments, and in addition, provides a meaningful scale for statistical analysis.

The neural coding of colour information has of necessity come from electrophysiological recordings in different species. In instances to be quoted, behavioural evidence of colour vision exists. Electrical recordings from the inner limbs of cones in the carp (TOMITA et al,/

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al, 1967) produced three forms of spectral response. The peaks of the response curves showed good agreement with the absorption data of MARKS (1965) in goldfish and gave further support for a functional division of cones into three groups.

When micro-electrodes were inserted between the receptors and the ganglion cell layer, a graded electrical response to a light stimulus was obtained. (This graded response from receptors and bipolars is to be contrasted with the typical all or none response from ganglion cells). The most frequently reported responses of this kind have come from work on fish (teleost) retinas, in which two fundamentally different types of graded electrical response (S-potentials) were found (SVAETICHIN and MacNICHOL, 1958). One type of response to light produced a negative potential at all wavelengths, with a broad band spectral response peaking between 500 and 600 nm. This was called the luminosity or (L) response, as its amplitude correlated with stimulus intensity. (In general the amplitude of S-potentials varied linearly with the logarithm of stimulus intensity). The second type of response showed both positive and negative potential changes, depending on the wavelength of the light stimulus. This chromaticity response was called the (C) potential. It was characterised by two maxima of opposite polarity in the spectral response wave. The maxima were found /

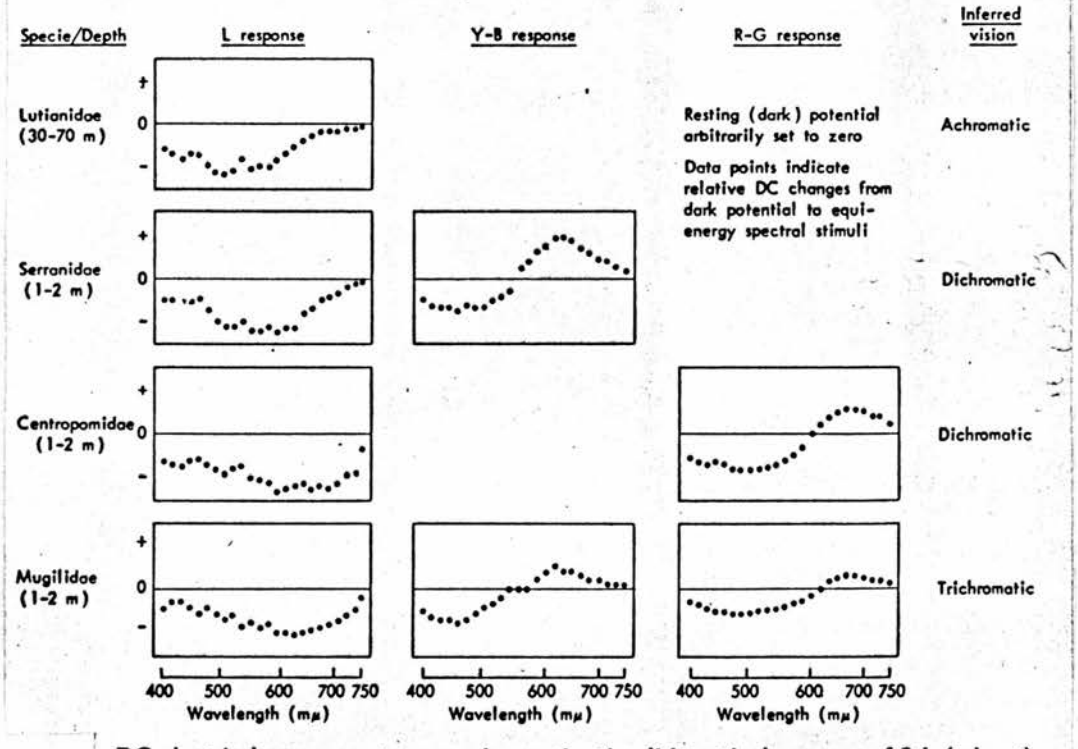


Figure 14 —DC electrical responses to monochromatic stimuli in retinal neurons of fish (teleost)

found to be in either the red and green (R-G) spectral regions, or the yellow and blue (Y-B) spectral regions. Both varieties had a spectral neutral point in which longer wavelengths tended to give positive potential changes, and shorter wavelength negative potential changes. (See Fig.14). These findings have been extended by NAKA and RUSTHTON (1966) to fish (tench) retina, where two classes of cone were seen to be responsible for each C-unit. One gave the positive potential change; one the negative potential change. On the other hand, contributions of the same polarity to the L-response were found to arise from three cone mechanisms.

These S-potentials were elicited by stimulation of a relatively large retinal area (7 sq. mm) and were produced by a combination of at least two cone systems. This meant that signals from the receptors must have converged on the cells responsible for the S-potential. At present, the large size of receptive field for these cells seems at variance with the fine spatial discrimination of human vision (RUDDOCK 1971).

Electrical recordings from ganglion cells provide the next source of information in the processing of visual data. It has already been pointed out that typical recordings at this level indicated that the visual coding must be carried by variations in the frequency of nerve firing, as the amplitude of the/

the "spikes" ramained constant. However, further studies showed that three principal types of ganglion cells existed. These were ON-units which fired at the onset of a light stimulus; OFF-units which fired when the light stimulus was turned off; and ON-OFF units which fired at both the onset and cessation of the light stimulus. Different cell types were associated with different retinal areas, so that the receptive field of an ON-OFF ganglion cell was divided into an inner and outer region, each with an approximately circular boundary. The signals from either region could be ON or OFF (excitatory or inhibitory) but whichever was the case, the neighbouring region was always opposite in effect, thus giving ON centre fields with OFF surrounds, and OFF centre fields with ON surrounds. (KUFFLER, 1953; BARLOW et al, 1957). Within any one type of region, the electrical response increased as the stimulus increased. However, if the response to light was recorded from one region, and a second light was added to the neighbouring region, the frequency of firing of the cell would decrease. The size of the inner region of a receptive field was smallest near to the fovea, and increased as one moved peripherally across the retina. This variation of receptive field size correlated with the size of light integration areas in psychophysical experiments (CRAWFORD and IKEDA, 1971). In addition Crawford and Ikeda suggested that the/

the nature of the ganglion cell organisation with adjacent areas resulting in opposite effects, could be important in increasing perceptual detail and diminishing the effect of stray light.

Studies on goldfish retina (WAGNER et al, 1963) have revealed cells with a similar nature but in addition the neural coding contained information about wavelength. Cells were discovered which were inhibited by red light and excited by blue-green light. This response was related to the area of stimulation so that a red light produced an OFF response in an inner receptive field region, an ON-OFF response in a neighbouring region, and finally an ON response as the stimulus was moved from the receptive field centre outwards. While evidence has been found in mammals for similar types of unit organised for particular red-green responses (HUBEL and WIESEL, 1960), there is little evidence in either fish or mammals for the yellow-blue unit which would correspond to the yellow-blue S-potentials. (RUDDOCK 1971).

2. The Lateral Geniculate Nucleus

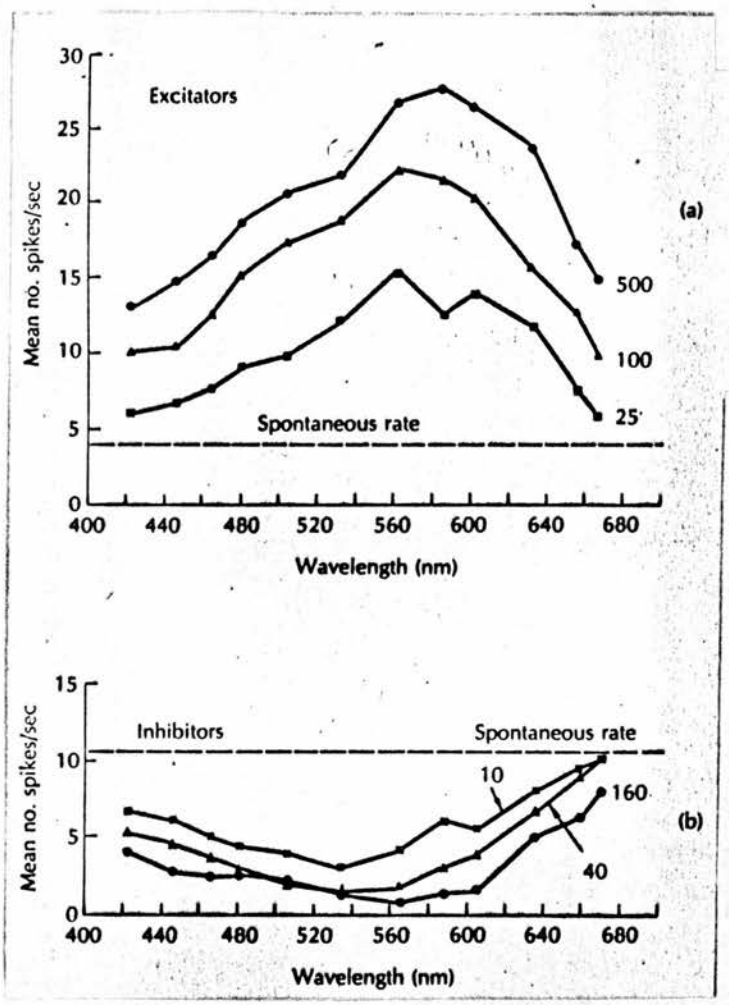
The next major stage of the visual system is the lateral geniculate nucleus (LGN) which has been studied extensively in primates by DE VALOIS et al (1966). Particular interest was devoted to these results as De Valois was able to show by psychophysical means that/

that the macaque monkey on which these experiments were carried out was trichromatic (i.e. had a colour vision system comparable to that of humans). The lateral geniculate nucleus receives the axons from the retinal ganglion cells (optic nerve fibres) and is divided into two sections with six layers each. Each section has three layers subserving the contralateral and three layers subserving the ipselateral eye.

In the dorsal layer, De Valois found that most cells fired at the onset of the stimulus (ON cells). Those cells which were related to the foveal region of the retina had narrow spectral response curves. Five types of such cells were distinguished, three of which predominated in the foveal region and had peak sensitivities at 550, 590 and 620 nm. While the peak sensitivity of these three was unaffected by adaptational changes, many cells in the peripheral regions showed a shift in peak sensitivity as the adaptational level changed.

In the ventral layers of the LGN only OFF cells were found. These cells showed a high spontaneous rate of discharge which was inhibited when the light stimulus was switched on. The inhibition was followed by firing when the light was switched off. Although a few of these cells had narrow spectral response curves, the majority had broad band curves with peaks at either 505 or 550 nm. or both. (These peaks are/

Figure 15



Average responses of non-opponent cells in the brain of the monkey. The units fire continuously at the rate labeled "spontaneous rate" until the eye is flooded with light of the wavelengths on the horizontal axis. The excitatory units in (a) respond to the stimulus by increasing their firing rates and the inhibitory units in (b) by reducing their firing rates. The three curves in each plot are three different intensity (energy) levels, in arbitrary units. [*From DeValois et al. (1966).*]

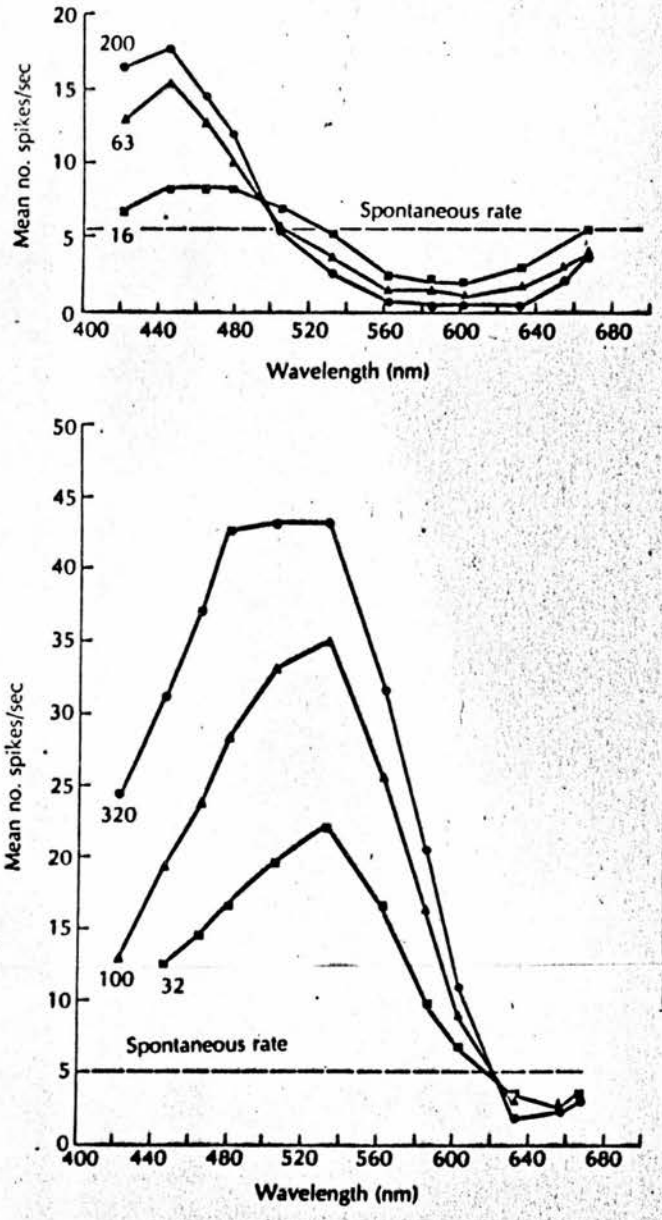


Figure 16

Average responses of various classes of spectrally opponent cells in the brain of the monkey. The three curves in each plot are three different intensity (energy) levels, in arbitrary units. (*From DeValois et al. (1966).*)

are very close to those of the photopic and scotopic luminosity functions). Cells in either the dorsal or ventral layers responded in the same way within a layer to all wavelengths, and were called non-opponent cells (See Fig.15). They were either all excitatory or all inhibitory. (Such units may carry intensity information in that the spectral response from non-opponent cells would look like Fig.15a. if either 3,2 or 1 cone types excited such a cell, or like Fig.15b. if either 3,2 or 1 cone types inhibited such a cell).

In the middle layer of the LGN, ON and OFF cells were found where the nature of firing was determined by the wavelength of the stimulating light. These spectrally opponent cells were excited by some wavelengths and inhibited by others. (See Fig. 16 and 17). More recent experiments on adaptational effects on opponent cells (DE VALOIS, JACOBS, 1968), have shown that these cells can be distinguished and classified into one of four principal categories:-

1. Excited by the cone system peaking at 580 nm.:
   and inhibited by cone system peaking at 550 nm.
2. Inhibited by the cone system peaking at 580 nm:
   and excited by cone system peaking at 550 nm.
3. Excited by the cone system peaking at 580 nm:
   and inhibited by cone system peaking at 435 nm.
4. Inhibited by the cone system peaking at 580 nm:/

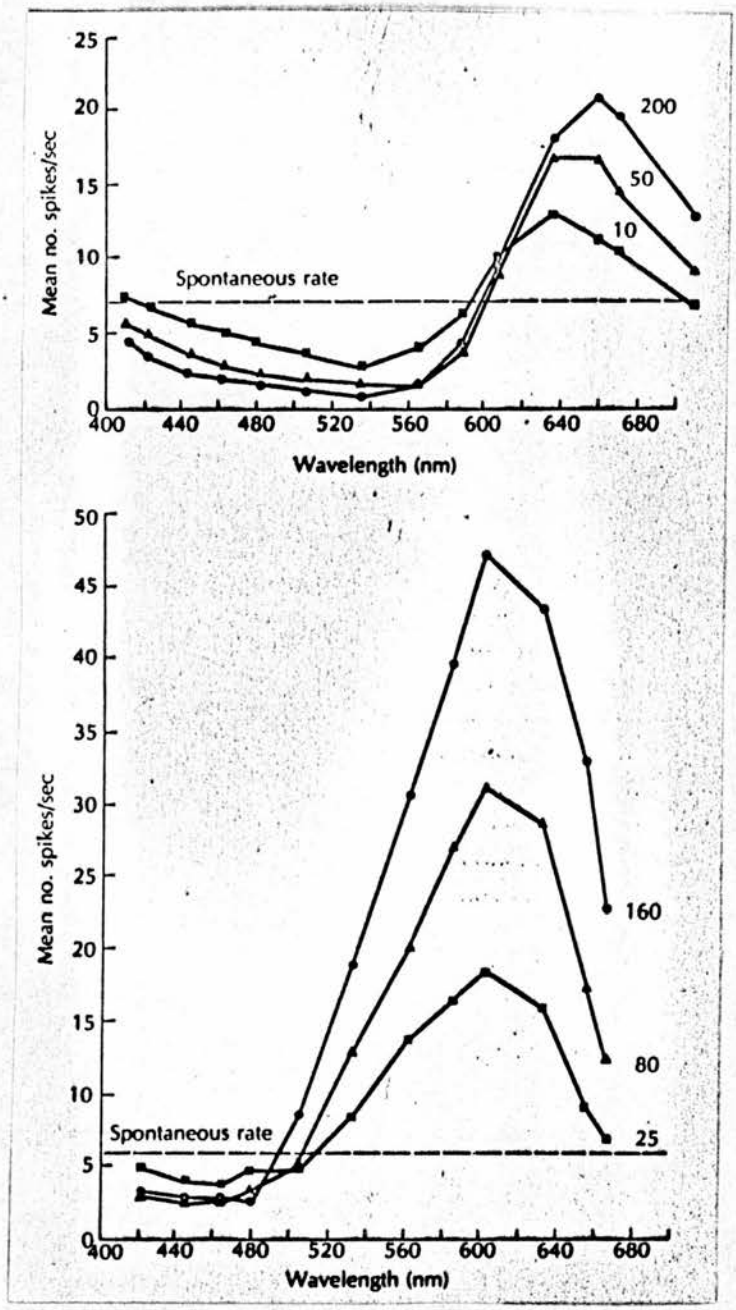

Mean no. spikes/sec
25
20
15
10
5
0
Spontaneous rate
200
50
10
400
440
480
520
560
600
640
680
Wavelength (nm)
Mean no. spikes/sec
50
45
40
35
30
25
20
15
10
5
0
Spontaneous rate
160
80
25
400
440
480
520
560
600
640
680
Wavelength (nm)

Figure 17

580 nm: and excited by cone system peaking at 435 nm.

Because of quantitative differences in the strength of either excitation or of inhibition, a wide variety of response curves resulted (Figs. 16 and 17). In general the opponent cells could be classified as either (+ R-G), (-R+G); or (+Y-B), (-Y+B). The non-opponent cells responded with a spectral response in close agreement with the photopic spectral sensitivity functions. Further variation in response was found to be related to change in retinal position.

3. The Visual Cortex

The termination of impulses from the visual system would appear to be the occipital lobes of the cortex. The axons terminating here arise from the lateral geniculate nuclei. Knowledge of function in this cortical area is much less than that for earlier stages of the visual pathway.

A most important feature of the visual cortex is the areal distribution of neural projections from the retina. The fovea of the retina of higher animals which represents 0.1% of the area of the external visual field, occupies over 80% of the cells in the visual cortex. The rest of the visual field terminates in only 20% of the cortex. Because of this distribution, one of the methods of assessing cortical function which is/

is the visual evoked response(V.E.R.), is predominantly a cone response. (This is a gross electrical response similar to the E.R.G.). Several practical limitations make V.E.R. recordings difficult, but it is as a correlate between human vision and microelectrode recordings from animal vision that its main importance lies. Instances to date of these correlations are in studies of binocular enhancement, colour coding, enhancement of responses by refractive correction, and enhancement of responses by attention arousal (CRAWFORD, 1971).

Microelectrode recordings from visual cortical cells, have been found to be extremely difficult to carry out. A particular feature of this difficulty is that the stimulus has to be well above the 'threshold' in psychophysical terms to elicit a response, and a great deal of noise detectable by the electrodes must be eliminated. Nevertheless, responses to different wavelengths of the opponent cell type were found, and cells were also found which responded with ON signals to a restricted range of wavelengths. A third type of response was of the ON and OFF type to all wavelengths. (MOTOKAWA et al, 1962). Cells of this latter type were tentatively identified as either photopic or scotopic luminous units as their spectral sensitivity was similar to human rod and cone function.

A further type of cortical cell was identified by ANDERSON, (1962). Here the response was of the non-/

non-opponent type with a narrow wavelength band. In addition the temporal latency between retinal stimulation and cortical response varied with the spectral sensitivity of the cell. Similar observations were noted in psychophysical studies (PIERON, 1952). The response to different coloured signals varied in a way suggesting that the transmission times to the cortex varied with stimulus wavelengths.

A most important series of experiments on the visual mechanism of the cat (HUBEL and WIESEL, 1959, 1962, 1965) has demonstrated the nature of receptive fields for cortical cells. The ganglion cell receptive fields in the cat were found to be approximately circular with opposite centre and surround, so that On centres were associated with OFF surrounds and vice versa. The receptive fields of the LGN cells were found to be similar to those of ganglion cells and approximately circular in shape. However, cortical cells (area 17 of the cerebral cortex) showed more basic differences and were divided into two principal types, simple cells and complex cells. Simple cells had receptive fields very similar to ganglion cells but elongated into a thin elliptical shaped central region with a parallel surround. As summation of light occurred within any region, such cells gave maximal response to a line in the visual field coinciding with the particular orientation of the ellipse, and hardly any response when both centre and/

and surround of the receptive field were stimulated. Hubel and Wiesel proposed that the function of such cells would be explained if their inputs were a set of geniculate fibres whose receptive fields were all in a row.

The complex cell responded to a particular line in a particular orientation irrespective of where it lay in the visual field within an area of about 5^{o}. Such cells contained information about slant but had lost information about location in space. Hubel and Wiesel proposed that the function of complex cells could be explained if their inputs were a set of simple cortical cells whose elongated receptive fields were adjacent and parallel. Further types of complex cell have been reported (HUBEL and WIESEL, 1965) in which a maximum response occurred for right angled figures (corner detectors). There was also evidence for the existence of cortical units which preferentially signalled movement across the visual field in a particular direction, (BARLOW and LEVICK, 1965).

However, a cautionary note must be added regarding the extrapolation of such findings to human vision. As Crawford and Ikeda, 1971, state "We are still a long way from a complete correlation of the results of the two great domains of exploration of the nature of vision, psychophysics and neurophysics. It remains uncertain for instance to what extent such discoveries/

discoveries as the phenomena of receptive fields, units sensitive to direction of motion, units selective with respect to orientation etc. can be assumed to hold for human vision. The design of psychophysical experiments to correlate with these and other neurophysical phenomena has only just begun and may well prove the most fruitful immediate source of further knowledge of the mechanism of human vision."

A brief sketch has been given of the physiological evidence which directly and indirectly suggests the nature of the mechanisms of normal vision. Much of this research was stimulated by evidence from psychophysical studies, some of which has already been presented in sections IIIa) and IIIc). Attention will be given in the following section to the nature of psychophysical evidence, to luminosity curves and colour matching experiments, and to the development of the notion of a standard observer.

IIId) Psychophysics

1. The Nature of Psychophysical Evidence

Reference to the nature of psychophysical measurement has been made in the introductory section and in the section dealing with specific psychophysical methodology. However, before dealing with purely psychophysical data, some mention must be made of the relationship of this evidence to physiology. In/

In particular it is the relationship between the subjective report of an individual regarding his sensations, and the objective physiological evidence which is of particular interest.

The formulation of physiological hypothesis is in physico-chemical or anatomical terms, which is in accordance with the background nature of theory underlying physiological measurement. It is difficult therefore, to see how a hypothesis which is stated in these terms can predict the results of experiments in which subjective reports of sensations are included. If such a hypothesis is to predict the results from a sensory experiment, then it would appear that the underlying theory must be expanded to include hypotheses which do contain psychological terms as well as the physico-chemical and anatomical terms. These additional hypotheses have been called psychophysical linking hypotheses (BRINDLEY, 1960).

The most acceptable and most general of such hypotheses proposed to date is that "whenever two stimuli cause physically indistinguishable signals to be sent from the sense organs to the brain, the sensations produced by these stimuli as reported by the subject in words, symbols or actions must also be indistinguishable." This was for Brindley the hypothesis which is "most difficult to doubt", and for him the only one which was "sufficiently secure to include/

include in the body of generally accepted theory". By its inclusion predictions of indistinguishability could be made, and used for testing further physiological hypothesis.

Brindley divided psychophysical experiments into two classes, A and B. Class A experiments which assumed this general hypothesis included matching experiments and absolute and incremental threshold determinations. In general any experiment which demonstrated that two stimuli under particular conditions produced either the same or different sensations was in Class A. Class B was reserved for all other observations, not in Class A, which could not be expressed as an identity or non-identity. All qualitative and quantitative descriptions of sensation belonged to Class B. Brindley thought that physiologists often adopted a conservative approach in which only information from Class A experiments was seen to be of value. On the other hand psychologists were seen to take a more liberal approach and admit both Class A and B experiments in formulating hypotheses about visual mechanisms and phenomena. Brindley illustrated ways in which certain Class B experiments could be converted into Class A experiments and so rest on a firmer hypothetico deductive structure.

While Brindley had formulated the nature of the problem of the relationship of psychophysics to physiology/

physiology, the particular psychophysical linking hypothesis he chose as being "difficult to doubt", and the validity of the Class A, Class B dichotomy received criticism (BOYNTON and ONLEY, 1962).

According to these authors it was doubtful whether Class A observations in themselves were a sufficient condition for assuming the psychophysical linking hypotheses, and some counter instances were quoted. Furthermore, in conditions when such a hypothesis was testable by Class A observations, the hypothesis which was really tested was the converse of Brindley's, namely, "Whenever the sensations produced by two lights are subjectively indistinguishable in every way, one may conclude that the stimuli which produce these sensations caused physically indistinguishable signals to be sent from the sense organs to the brain".

Based on this new hypothesis, Boynton and Onley proposed an extension of the Class A, Class B dichotomy into six categories.

Under Class A observations there were:-

1. Those for which the new hypothesis was probably true on other evidence. (Examples given were scotopic absolute thresholds at different wavelengths; brightness matching of very small areas of different size; non-metameric brightness matching of stimuli with the same physical characteristics)./

characteristics).

2. Those where the new hypothesis was debatable in the light of other evidence. (Examples given were brightness matching where the stimuli were large enough to produce differing light distributions on a retinal region where there was complete summation).
3. Cases where the new hypothesis was probably not true. (Examples given were photopic threshold measurements at different wavelengths and some increment threshold measurements, where the test spot and background had physically the same energy distributions but when changes in adaptation level resulted in the stimulation of different mechanisms).

Under Class B observations were:-

1. Cases where matching was achieved on one variable but where other variables remained different between the matched pair of stimuli. (Examples given were heterochromatic brightness matching; perceptual experiments where illusions were measured by matches of apparent size).
2. Cases where quantitative estimates of some psychological aspect of the stimulus were assessed. (Examples were brightness scaling; equal spacing of colour space; subjective/

subjective stimulus of the size illusions).

3. Cases where qualitative estimates of a stimulus were made. (Examples were Maxwell's spot, Haidinger's Brushes, Purkinjie shift, simultaneous and successive colour contrast experiments, and experiments where illusions were described but not quantified).

Boynton and Onley consider that in the majority of psychophysical experiments it is not clear whether the truth of a psychophysical linking hypothesis is being tested, or assumed. This suggests a more tenuous relationship between psychophysics and physiology which may be the "essential nature of the subject ultimately attributable to the uncertain relation between physiological events and conscious experience".

Nevertheless, the importance of the system is in the delimitation of Class A experiments and in the clarification of assumptions and inferences relating to any psychophysical experiment. Most of the experiments carried out in this report are in Class A although in the extended system they fall into the three subdivisions listed above. In addition, attempts are made to use Class A methodology wherever possible. Reference to this system will be made when each test is presented.

2. Luminosity Curves/

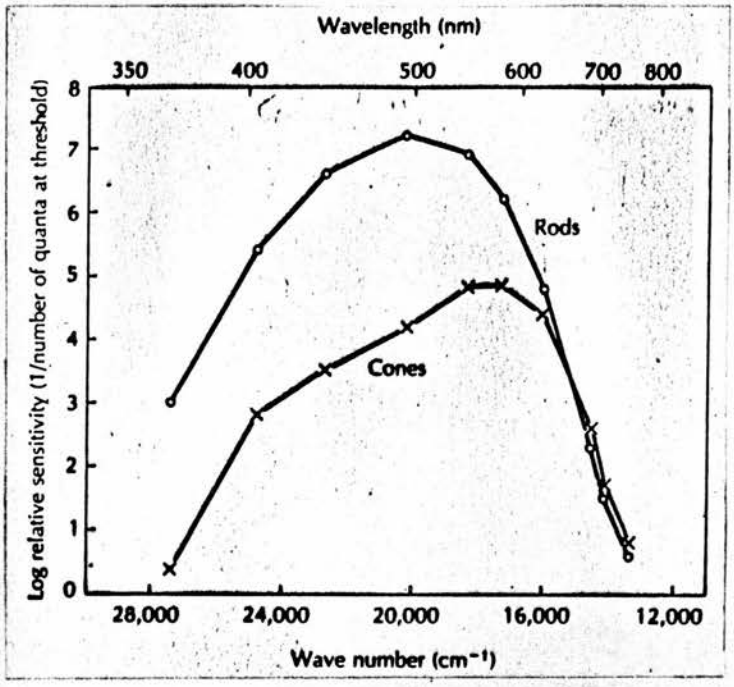


Figure 18 Photopic (cone) and scotopic (rod) spectral sensitivity curves. [*After Wald (1945).*]

2. Luminosity Curves

The experimental methods which have been used to determine both scotopic and photopic luminous efficiency curves are:-

a. Absolute threshold measurements.

b. Heterochromatic brightness matching.

c. Flicker photometry.

In the first method the stimulus energy is increased until perception occurs. The relative sensitivity is obtained as the reciprocal of flash energy required to elicit seeing. In the second method, brightness matching of two stimuli with different wavelengths is carried out. In the third method two stimuli of different wavelengths replace each other in the field of view at a rate of around fifteen flashes/sec. The flicker produced depends on the intensities of the two stimuli which are adjusted until the flicker is at a minimum, and the reciprocal of the intensities at minimum flicker is used to establish the relative sensitivity. This method which is probably the simplest from the patient's viewpoint, was chosen to determine the luminosity curves in Section V.

The scotopic and photopic functions as measured by the absolute threshold method are shown in Fig. 18. The scotopic function has a maximum sensitivity at 505 nm. and the photopic at 555 nm. Two general features to be noted are firstly, that the rods are more sensitive/

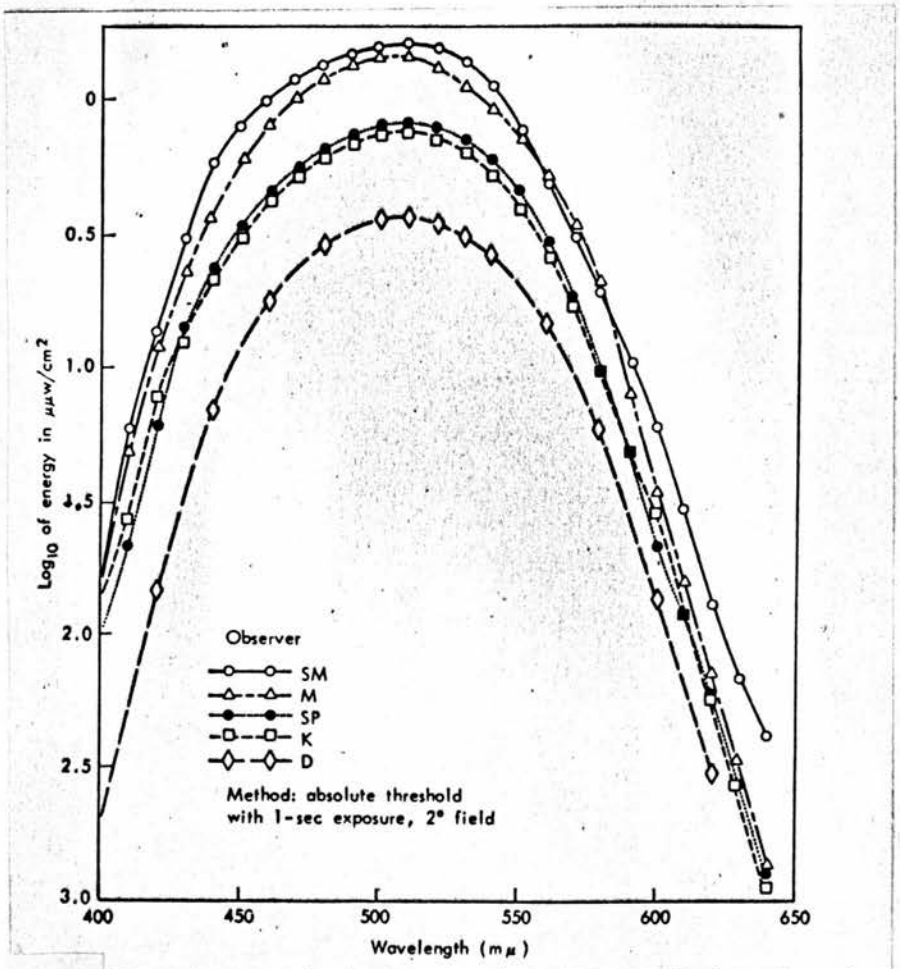
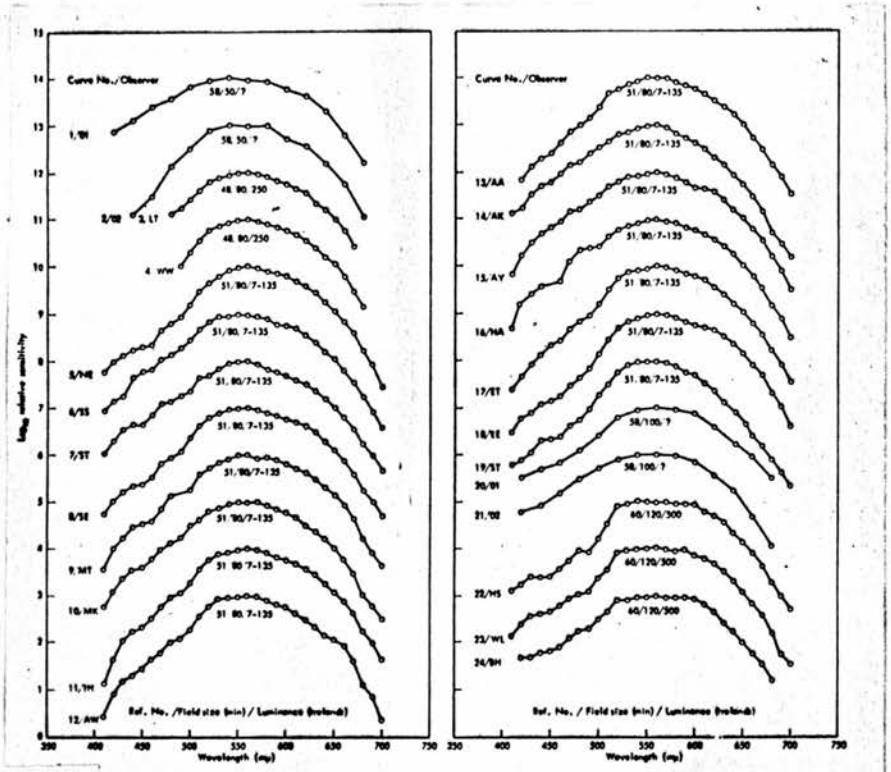
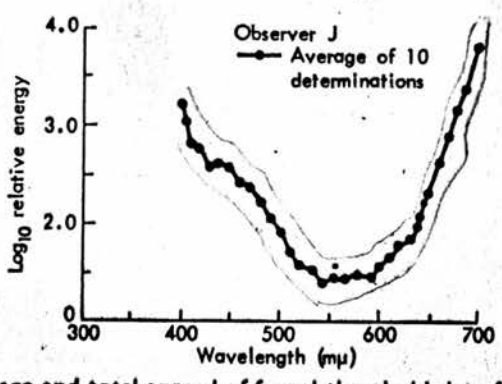


Figure 19 —Measurements of scotopic spectral sensitivity at 10° from fovea by Kinney



-Individual foveal spectral sensitivity determinations by the flicker method

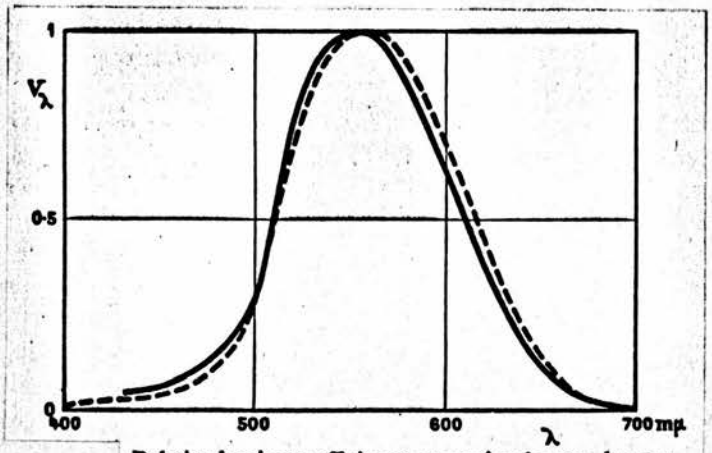


-Average and total spread of foveal threshold data for one subject by Hurvich and Jameson

Figure 20

sensitive to light than cones in all wavelength regions other than at the red end of the spectrum. Secondly, the scotopic curve is much smoother than the photopic. (This is in keeping with the assumption that one receptor mechanism underlies scotopic function - see page 40). Individual variations in scotopic sensitivity are shown in Fig. 19. While this variation is significant, the differences are of a simple nature so that the relative threshold sensitivity is fairly constant among individuals. As the light adaptational level is increased from scotopic to photopic levels, visual sensitivity changes from the scotopic curve through an intermediate mesopic region to the photopic curve.

The mesopic function is broad and is highly dependent on adaptational level. It also exhibits 'humps' which are present in the photopic function, and are presumably due to cone intervention as the adaptational level is increased. The photopic sensitivity curve is of great interest as the irregularities in it are probably manifestations of the underlying cone mechanisms. Unfortunately, the irregularities are highly dependent on experimental conditions and the resulting curves differ widely between one individual and another. Moreover, considerable scatter can be seen in the repeated measurement of one subject, (See Fig. 20), which casts doubt on the/



Relative luminous efficiency curves by the step-by-step method (——) and the flicker method (----)

Figure 21

the validity of the irregularities. Frequently the experimental error is of the same order of magnitude as the size of an irregularity (COLLINS, 1961).

It has also been observed that different methods of testing produce differing photopic curves so that the flicker and step-by-step heterochromatic matching method, do not produce comparable date (Fig.21). Fig.20 gives some idea of the individual variation which is produced by field size and position, flash duration, lumination level, adaptation conditions.

A general conclusion from the mass of data on luminosity curves was that any irregularities were enhanced by using very small fields of view and monochromatic stimuli (SHEPPARD, 1968). A further general finding was that the sensitivity to light was decreased as the field size was decreased (SPERLING and LEWIS, 1959; LA DRIERE, 1961). This decrease in sensitivity was within the rod free area of the fovea and was not due to the lack of functioning rods as the field size was reduced. (LA DRIERE,(1961), BEDFORD and WYSZECKI(1958) showed that rod effects were absent at subtences less than 80' of the central fovea). Decrease in blue sensitivity was observed as the field size was reduced through 75', 50', 25', 5'. This effect, known as small field tritanopia, (See page 93) had additional support from matching experiments by WILLMER and WRIGHT (1945). However, the decrease in/

in blue sensitivity could be counteracted in small fields by raising the stimulus intensity level. (BEDFORD and WYSZECKI 1958, LA DRIERE, 1961). The problem was further confused by fixation difficulties encountered with fields of this size.

The variabilities and irregularities of the photopic sensitivity curve remain unexplained. All attempts to account for the function as a linear combination of three or four different primary cone mechanisms have failed. (HURVICH and JAMESON, 1953, 1954; BOYNTON, KANDEL and ONLEY, 1959; STILES, 1946). (The predominance of the number three, and the linearity of the combination is suggested by matching experiments). BOYNTON (1963) has recently shown that receptor theories with three or four fundamentals which include linearity and summation, cannot account for the photopic sensitivity curve. The non linear transformation occurring after the initial absorption of quanta by the photopigment influences both temporal and spatial summation, and must play a crucial role in any model of human colour vision.

3. Matching Experiments

These experiments have played a major role in promoting the search for photopigments in the retina (see page 45). The procedure is to arrange a photometric field of up to 2^{o} overall diameter and to/

to divide it into two equal halves. If a test stimulus is added to one half of the photometric field the problem is to find the minimum number of coloured components necessary to make the two halves of the field match. Such matches are called metameric, when two different spectral energy distributors produce the same colour sensations. The components must be mixed in an additive fashion; i.e. a condition that is met when a set of coloured lights are superimposed on each other in the field of view. This is the principal of the anomaloscope (page 179).

In general, it has been found that if a person with normal vision views the photometric field, a test stimulus of any spectral composition can be matched by a suitable mixture of at most three fixed monochromatic stimuli. The amounts of the three necessary to match a standard stimuli vary from observer to observer, but three are always sufficient. The choice of three primary monochromatic stimuli is to some extent arbitrary as there are many sets of three which will suffice to give a match. Occasionally, depending on the test stimulus and the three primaries, it is necessary to add one of the primaries to the test stimulus to obtain a match. Such instances of negative addition do not indicate a loss of generality. The important point is that with three stimuli a match can always be made. There are two principal limiting/

limiting conditions on the sets of three matching stimuli. Firstly, no one stimulus must be matched by a mixture of the other two. Secondly, some combination of the three matching stimuli must give white light. These conditions follow from a series of experiments carried out by GRASSMAN (1853), who formulated laws governing colour mixtures. The experiments showed that the stimuli forming a metameric match could be considered as elements in an algebraic equation obeying algebraic rules.

For instance a colour match between a test stimulus C and matching stimuli C_1, C_2, C_3, could be represented as:-

$$L(C) = L_1(C_1) + L_2(C_2) + L_3(C_3)$$

indicating that L units of light stimulus C are identical in appearance with a mixture of L_1 units of matching stimulus C_1, L_2 units of stimulus C_2, and L_3 units of stimulus C_3. (L, L_1, L_2, L_3, are normally expressed in terms of the luminance of the visual field).

If a second match was obtained using a different test stimulus but the same matching stimuli to give:

$$L'(C') = L_4(C_1) + L_5(C_2) + L_6(C_3) ,$$

it was found that when the left hand stimuli were mixed to give the further match:

$$L(C) + L'(C') = L_7(C_1) + L_8(C_2) + L_9(C_3)$$

then, $L_7 = L_1 + L_4$; $L_8 = L_2 + L_5$; $L_9 = L_3 + L_6$

This/

This is the principle of additivity of colour matching. (See Abney's Law page 77) If both sides of the metameric equation are increased or decreased by the same term, or if all terms in the equation are multiplied by the same factor, then the two halves of the photometric field match over a wide range of experimental conditions. It follows that any sum of monochromatic luminances (therefore any continuous spectrum or complex set of radiations) can always be matched by adjustment of three variables. This experimental fact is known as the trivariance of vision. It has been assumed that the three matching stimuli are monochromatic, but this need not necessarily be so, although it is in general, the case. With the possibility of reducing complex radiations to equivalent stimuli having only three independent variables, the three variables can be used as a means of specifying colour. Although there is no unique set of three matching stimuli it is common to choose one from the red, one from the green and one from the blue parts of the spectrum.

One such set of matching stimuli chosen by WRIGHT (1946) was:

C_1 = 460 nm.; C_2 = 530 nm.; C_3 = 650 nm.

The relative values of the three stimuli required to match any other monochromatic stimuli were known as the distribution coefficients. These are plotted/

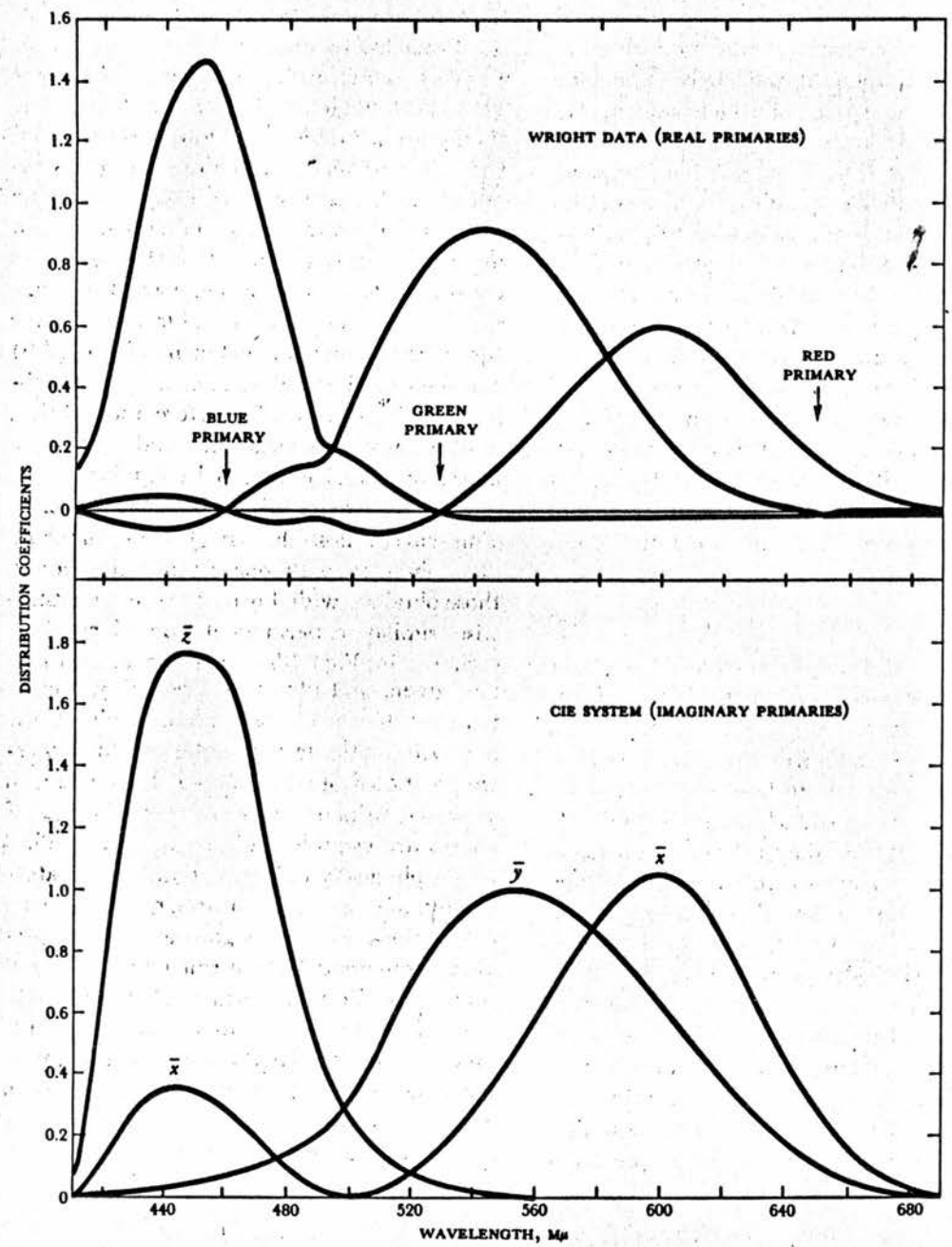


Figure 22 **Distribution coefficients describing the results of a real experiment in color mixture for primaries shown (upper curves) and transformed data adopted by the CIE (lower curves).**

plotted in Fig.22 after WRIGHT (1946). The curves vary as the primaries vary but it can be shown that for a given observer the sets of such curves generated from different matching stimuli are linearly related.

The outcome of the matching experiments is:-

a. Normal human vision is trivariant. Consequently, there must be a minimum of three independent systems for the coding of colour information whose outputs are at least partly separate throughout the visual system. The system, may be convergent with several independent channels preceding a three channel point but there must be three channels at some point in the visual system.

b. As there are many sets of three primaries, the spectral sensitivity of three physiological channels for colour coding can not be deduced from the matching data. However, the colour matching curves must be linearly related to these spectral sensitivities.

c. The additivity of the colour matches implies linearity in the visual system. As the electrophysiological evidence presented in Section III showed that a non linear transformation occurs very early in the pathway, the linearity is thought to exist at the photoreceptor level where the initial/

initial absorptions of quanta take place. This would be a sufficient condition to account for the colour matches no matter what the subsequent input/output characteristics of the channel might be.

4. The Standard Observer

The individual variation in both the scotopic and photopic luminosity curves and the somewhat arbitrary nature of the "primaries" in colour matching experiments, must be replaced by a standard system for the solution of many practical problems in photometry and colour specification. If a standard observer is defined, who replaces the variable human, then a set of luminous quantities may be defined from the physical quantities of radiance.

In 1931 the Commission Internationale de L'Eclairage (CIE) using the mean photopic relative luminous efficiency curve of over 200 observers (GIBSON and TYNDALL, 1923) defined the relative luminous efficiency curve of the standard observer. This observer was defined with respect to a 2° viewing field. If V_{λ} is the relative luminous efficiency function of the standard observer and Le is the source radiance, the appearance of the source depends on the product V_{λ} Le. This luminance L was defined as:-

$L = Km \; V_{\lambda} Le$ where Km is a constant/

constant.

When several lights were superimposed the resultant luminance was found to be the sum of the individual luminances, (ABNEY, 1913). This additive property of luminance gave experimental backing to the further definition of luminance for a group of monochromatic radiations or for continuous radiation. The extended definition of luminance was:

$L = Kn\int V_\lambda \, Le_\lambda \, d\lambda$ in which the limits of integration were set by the limits of the visible spectrum.

By analogy results of CRAWFORD (1949) and WALD (1945) were used to define the CIE scotopic luminous efficiency function in 1951. A new set of photometric quantities were then defined so that scotopic luminance L' was given by:

$L' = K'n\int V'_\lambda \, L'e_\lambda d\lambda$ where K'n is a constant.

V'_λ is the CIE scotopic luminous efficiency function of the standard observer and $L'e_\lambda$ is a spectral radiance sufficiently low for the Purkinjie effect to operate. Thus there are two separate definitions for the brightness response of the standard observer, one for photopic conditions, one for scotopic.

The next problem was to define a system for colour specification. For this the data of WRIGHT (1928) and GUILD, (1931) were averaged to form the basis of the colour mixture functions of the standard observer. The/

The curves were based on the primaries at wavelengths 700 nm., 546.1 nm., 435.8 nm. Unfortunately, it was found that with any set of 'real' primaries, some test stimulus could always be chosen which required a negative amount in one primary, i.e. the primary was added to the position of the photometric field containing the test stimulus. For this reason, and because any selected primaries might erroneously be thought to have physiological importance, the CIE decided on a system of colour specification based on imaginary primaries which were obtained by a transformation of the data of Wright and Guild. The transformation still enabled the colour mixture functions to be related to the vision of real observers, but now any stimulus could be specified by positive amounts of the three primaries. In addition for practical reasons, one of the distribution coefficients was made to coincide with the photopic $V\lambda$ curve of the standard observer so that this one coefficient carried all the information concerning luminosity. Finally the coefficients were chosen so that equal amounts of the three were equivalent to an equal energy white spectrum. This became the internationally accepted XYZ system.

A comparison of the real and imaginary primaries is shown in Fig. 22. The CIE distribution coefficients are represented by $\bar{x}_\lambda$ $\bar{y}_\lambda$ $\bar{z}_\lambda$. Monochromatic light of wavelength λ therefore, produces the same colour/

colour sensation as a mixture of the three primary colours in the proportion $\bar{x}_\lambda\ \bar{y}_\lambda\ \bar{z}_\lambda$. Colour specification is assessed as the function of the radiation of the light source ($E\lambda$), the reflectance characteristics of a surface ($R\lambda$) or the transmission characteristics of a filter ($T\lambda$), and the characteristics of the standard observer. The proportions of the primaries required to produce the colour of an object at a particular wavelength are given by three expressions $E\lambda R\lambda \bar{x}\lambda$; $E\lambda R\lambda \bar{y}\lambda$; $E\lambda R\lambda \bar{z}\lambda$. These expressions are determined at each wavelength and their sum over the visible range obtained, and X, Y, Z (known as tristimulus values) represent the three sums.

$$X = \int E\lambda R\lambda \bar{x}\lambda \, d\lambda$$
$$Y = \int E\lambda R\lambda \bar{y}\lambda \, d\lambda$$
$$Z = \int E\lambda R\lambda \bar{z}\lambda \, d\lambda$$

A colour is, therefore, defined by the three numbers X, Y, Z, and can be represented diagrammatically as a point in three dimensional space. However, it is the relative amounts of the tristimulus values which are used to form a two dimensional representation of colours, known as the chromaticity diagram. The chromaticity co-ordinates which are the reference co-ordinates for this diagram are defined as:-

$$x = \frac{X}{X + Y + Z} \qquad y = \frac{Y}{X + Y + Z} \qquad z = \frac{Z}{X + Y + Z}$$

As the sum of the co-ordinates is equal to one, only two co-ordinates are necessary to specify colour./

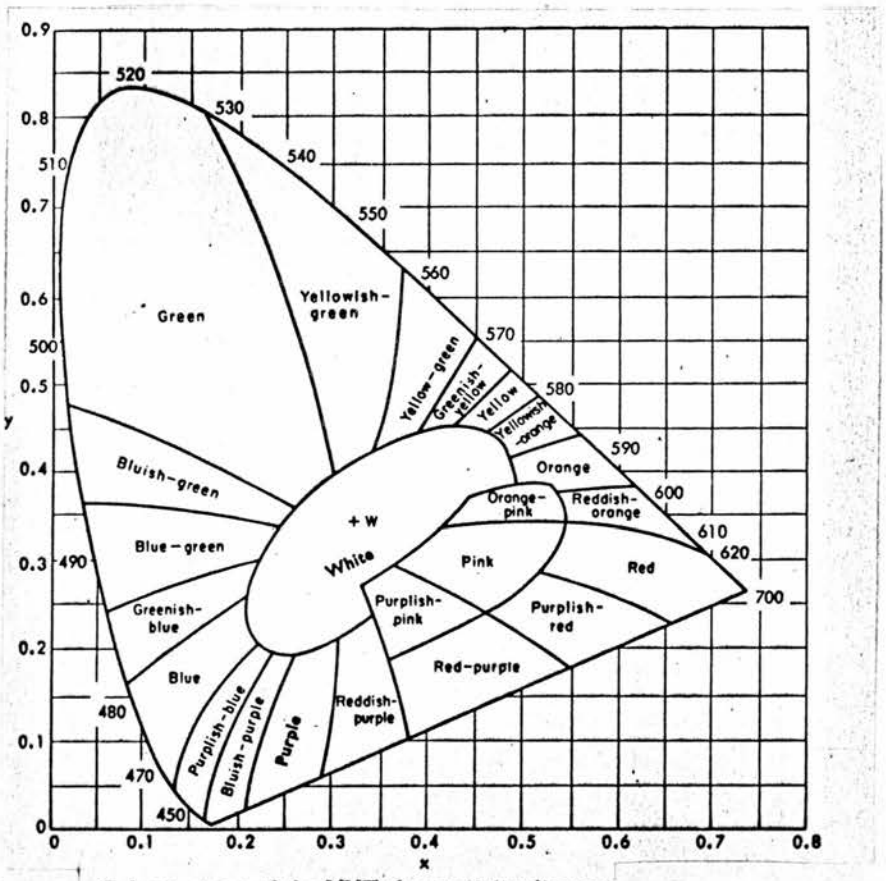


Figure 23 —Color regions of the XYZ chromaticity diagram

colour.

In the chromaticity diagram each position represents one type of colour. The co-ordinates x and y are plotted as shown in Fig.23 so that as the maximum value for x and y is 1.0 all colours must lie within the triangle. The pure spectral colours lie on the spectrum locus bordering the triangle, the line joining the extremes of the spectrum being called the purple line. The saturated colours (see below) lie near to the spectrum locus, and the desaturated colours and the achromatic point lie near the centre of the triangle. The CIE have defined several standards of white light which corresponds to the spectral emittance curves of a full radiator e.g. Standard A (2854°K), Standard B (4800°K), Standard C (6500°K). The x and y co-ordinates can be used to specify the hue but not the luminosity of a colour. For the luminosity a third dimension is added at right angles to the plane of the colour triangle thus making a three dimensional colour solid. The luminosity dimension is represented by the Y tristimulus valve which is frequently assessed as a percentage of that Y value for the test colour to the Y value for a standard white. It is customary, therefore, to specify colours by the three values x, y, Y.

Occasionally an alternative system is used which replaces the chromaticity co-ordinates(x, y) by the dominant wavelength and excitation purity. This/

This system is closely linked to the psychological attribute of colour called saturation, which indicates the departure of a colour from white. The dominant wavelength is the intersection of the spectrum locus by a straight line from the achromatic white point through the point representing the test colour. Excitation purity is the ratio of the distance from the achromatic point to the test stimulus over the distance of the achromatic point to the spectrum locus. In cases where the straight line intersects the purple line, the complementary dominant wavelength is used for specification i.e. the line is extended to the intersection of the spectrum locus on the other side of the white point. One of the most important characteristics of the colour triangle which follows from the laws of Abney and Grassman is that an additive mixture of any two colours lies on a straight line joining the two colours. Furthermore the distances between the point representing the mixture and the points representing the colours to be mixed are in inverse proportion to the amounts of the two colours in the mixture. This principle is of special importance in analysing and interpreting the anomaloscope results (page 179).

The luminosity curves and the matching data represent the visual properties of a standard observer on which all photometry and colorimetry are based. The CIE system,/

system, which has now gained international acceptance, will form the basis of any analysis of stimulus characteristics which are carried out in this report.

IV COLOUR VISION ANOMALIES

a.) Congenital Dyschromatopsias

The psychophysical evidence from the matching experiments (See page 71) demonstrated that an observer with normal vision required three independent variables to match any stimulus. Such observers were called trichromats. Because the CIE defined a standard observer with particularly exact characteristics, the individual variations of people with normal vision, although relatively small, resulted in random deviations from those of the standard observer. (The individual variation among normal trichromats within any age group is thought to be due to either variations in macular pigmentation, or small changes in the colour mixture curves. Assessments of these factors and the age variable itself on colour perception are discussed under acquired dyschromatopsias.)

On the other hand, however, colour vision anomalies constitute significant differences from those encompassed by the Gaussian curve of individual differences in normal trichromats. As there is relatively little known about the mechanism of colour anomalies, the systems of classification are based largely upon the performance of individuals on certain tests. The most common test in this respect is that comprising the photometric field which was used in the matching/

matching experiments. Such an instrument is a small colorimeter or anomaloscope, and matches on this instrument are perhaps the simplest way of describing the congenital dyschromatopsias.

1. Anomalous Trichromats

The anomalous trichromats require three stimuli to establish colour matches as do normal observers; however, the matches involve different amounts of the three primaries and are significantly different from those of the normal observer. The anomalous trichromats are divided into three principal types according to their colour matching characteristics. In a photometric field containing a mixture of red and green light to be matched against a yellow light, the deuteranomalous observer requires significantly more green in the mixture (displacement towards the green) to obtain a match. In the same situation the protanomalous observer requires significantly more red in the mixture (displacement towards the red) to match the fixed yellow. That the anomalous trichromats are distinct groups, and not extreme forms in a normal distribution, was shown by HOUSTON (1932) and FORSHAW (1954) in statistical studies. The deuteranomalous were certainly a distinct group although the situation was less clear regarding the protanomalous.

Protanomaly and deuteranomaly are both/

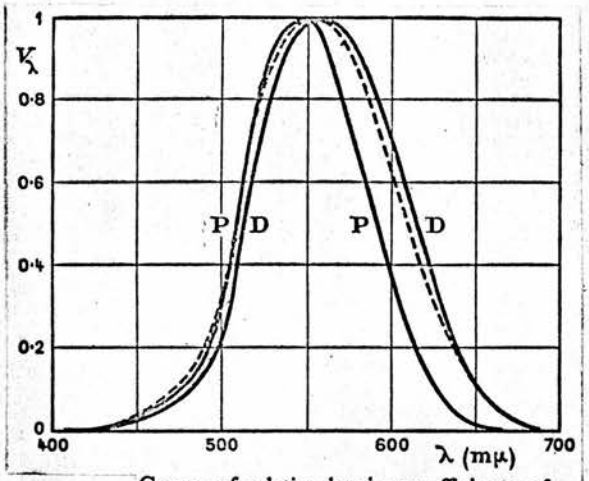


Figure 24 Curves of relative luminous efficiency of protanomalous (*P*) and deuteranomalous (*D*) subjects. The broken line curve refers to the average normal observer

both red-green anomalies. It is expected that by analogy an incomplete blue-green anomaly, tritanomaly, should also occur. This has been reported (COLE and WATKINS, 1967), but its existence is still debatable (FARNSWORTH, 1955; JAEGER, 1955). The tritanomalous observer who matches a blue standard by a mixture of violet-blue and blue-green (equation of Trendelenburg) requires too much violet-blue in the mixture in comparison with the normal observer.

It is assumed that anomalous trichromats have a different colour system, so that matches obtained by a normal observer appear wrong to the anomalous trichromat and vice versa. (Any pigmentation hypothesis can be ruled out, as they also have different vision in parafoveal regions.) While the scotopic luminous efficiency curve is normal, the photopic luminous efficiency curve is changed (See Fig. 24). Although in colour matching experiments the deuteranomalous differs from normal more than the protanomalous, the reverse is true regarding their luminosity curves. The shortening of the spectrum at the red end in protanomaly results in a shift of peak sensitivity down to approximately 545 nm. The deuteranomalous luminosity curve shows a slight inverse Purkinjie effect.

There are vast individual differences within the different types of anomalous trichromat as can be seen from Fig. 25 . Some individuals have very stable and/

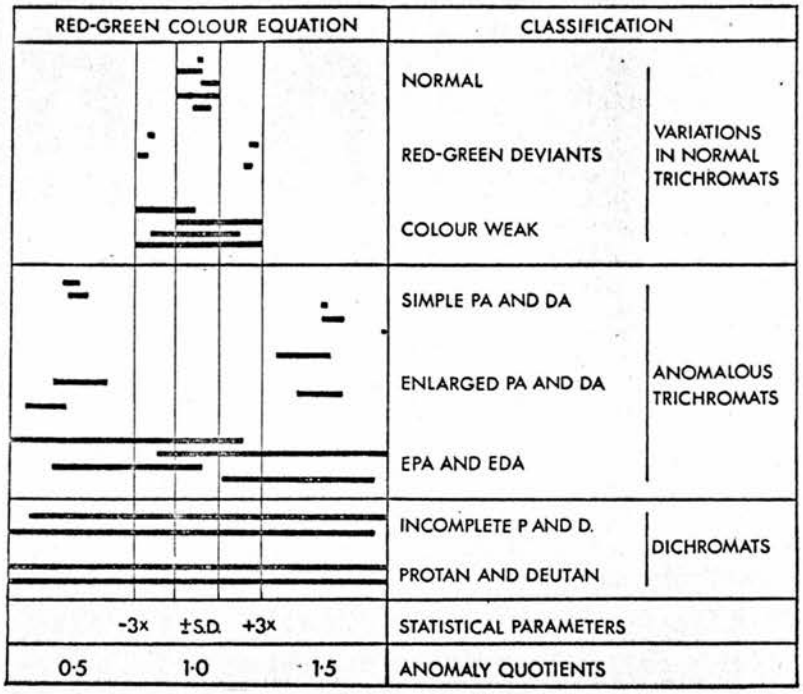


Figure 25 Graphical representation of red-green colour vision classifications yielded by anomaloscope data

and sensitive colour vision systems although different from normal (simple deuteranomalous DA and simple protanomalous PA). Their sensitivity is demonstrated by the fact that the number of mixture ratios which are acceptable as matching the standard (denoting matching range), is small. Their mid-matching point which is the representative or average mixture ratio is clearly outwith normal limits. (These two concepts of matching ranges and mid-matching points are the two most important parameters which can be obtained from anomaloscope data). (See page 179) The slight inverse Purkinjie effect in the case of the deuteranomalous type is not sufficient to prevent such individuals from being good photometric observers.

On the other hand, other individuals who are also classed as anomalous trichromats have large matching ranges and are almost dichromats (See following section). Their large matching ranges may extend into the normal region from the simple deuteranomalous or simple protanomalous points. Such individuals are called extreme deuteranomalous or extreme protanomalous. Again there are further variations within either of these categories as is shown in Fig. 25 . All these variations however, presuppose that three independent variables are a necessary condition for matching any set of test stimuli.

2. Dichromats/

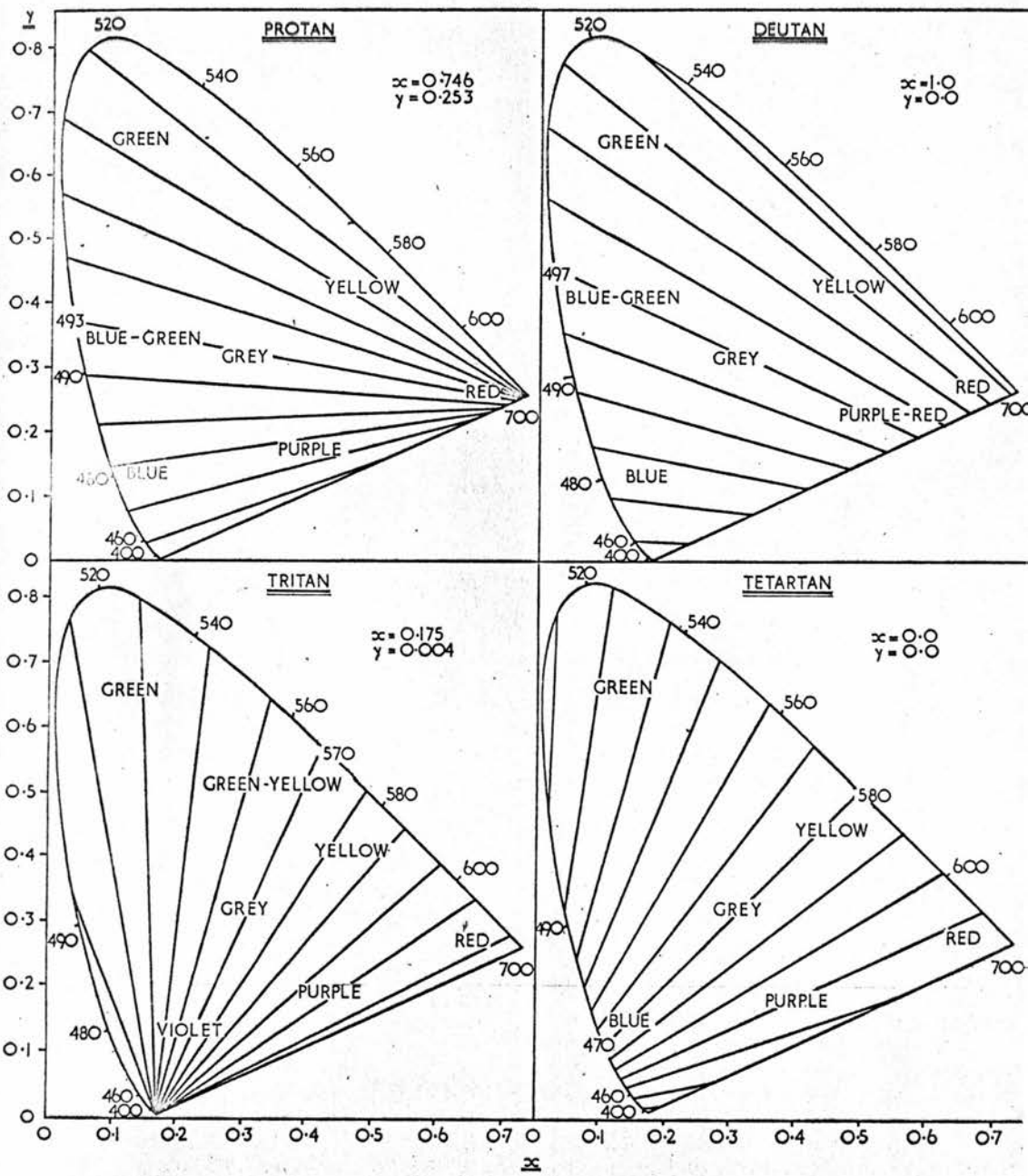


Figure 26 Confusion loci, centre of confusion, and neutral axes for dichromats.

2. Dichromats

This type of vision was first described by DALTON (1798), and the red-green variety named by VON KRIES (1897). In terms of the matching experiment, a dichromat requires only two stimuli in the additive mixture to match any test stimulus. Such observers will accept the matches set by normal observers but will in addition confuse many colours which are distinguishable by individuals with normal vision. The three principal types of dichromat are the protanope, deuteranope and tritanope. A fourth type, the tetartanope, has been suggested (MEULLER, 1924; JUDD, 1944) but its existence is questioned. Such a defect may result from a tritanope with heavy macular pigmentation. (WALLS and MATHEWS, 1952; ASPINALL, 1968). Both the protanopes and the deuteranopes confuse all monochromatic stimuli from 530 nm. upwards into the red end of the spectrum. Tritanopes confuse all blue, blue-green, and green spectral stimuli between approximately 460 nm. and 520 nm.

As the dichromat accepts the colour matches of normal observers, it is possible to derive the dichromatic colour matches from these by assuming that some power of colour discrimination has been lost while the remaining mechanisms remain similar to those in normal observers. This assumption leads to the development of dichromatic confusion lines (See Fig. 26) which indicate those stimuli lying in the plane of the paper (and consequently/

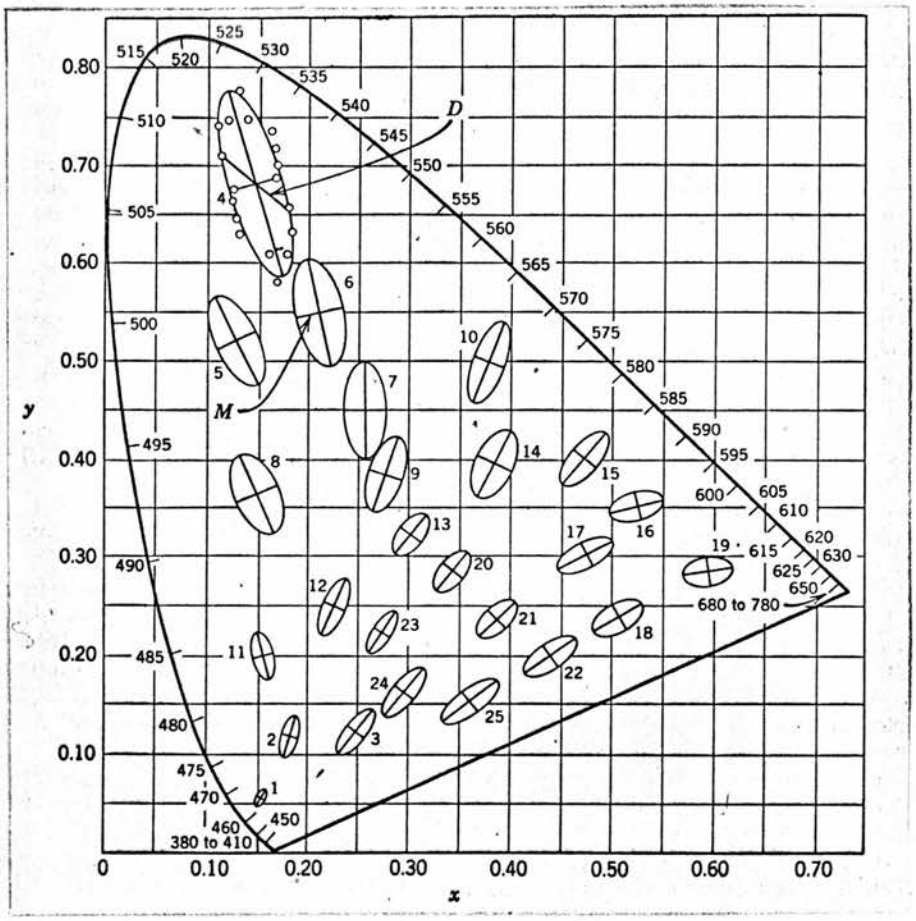


Figure 27 The MacAdam ellipses (1942). Each ellipse is drawn through points representing ten times the standard deviation of settings for chromaticity matches obtained by the method of average error. Standard deviation of settings were determined along several straight lines D, radiating from M, the central points. (After Le Grand, 1957).

consequently of the same luminance) which will be confused by the various forms of dichromat. These isochromatic lines while slightly idealised are of great practical value, and represent the general direction of dichromatic colour confusion (subject to slight individual variation). Each set of isochromatic lines have a common point of origin known as the centre of confusion or copunctal point. The xy co-ordinates of this point for the three dichromatic types (after PITT, 1935; and FARNSWORTH, 1954), are:-

Protanopes	xp = 0.747	yp = 0.253
Deuteranopes	xd = 1.08	yd =-0.08
Tritanopes	xt = .170	yt = 0.00

Each dichromat has a neutral axis indicating the colours to be confused with white, and particularly the monochromatic stimulus that is equivalent to white. This is approximately 495 nm. for protanopes, 500 nm. for deuteranopes and 570 nm. for tritanopes, for a white standard of 4800°K (PITT, 1935).

The dichromatic confusions are put in perspective by a consideration of the separation between stimuli necessary for the appreciation of a colour difference by normal observers. Two stimuli of equal luminance are distinguishable if the distance between their xy co-ordinates exceeds a small value given by MacAdam ellipses (See Fig. 27). Conversely, areas within an ellipse are indistinguishable to a normal observer./

observer. (Note: (i) the arbitrary nature of the definition of colour sensitivity as ten standard deviations of a colour match setting, and (ii) the variation in size of ellipse in different regions of colour space.) By comparison, for the dichromat, the size of the ellipses are of little consequence in relation to the substantial losses shown by the confusion lines. Nevertheless one can assume that the extent of an ellipse axis at right angles to a confusion line, also applies to the dichromat and is an indication of his colour discrimination in this particular direction. The line perpendicular to the neutral axis extends to the saturated yellow on the one side and into the blues on the other side, and these colours represent the ones which the deuteranope and protanope can distinguish. Similarly the tritanope is capable of distinguishing colours into the green on the one hand, and into the red on the other.

The anomaloscope detection of dichromats is straightforward, as they accept all mixtures in matching the standard yellow (See Fig. 25). However, the distinction between protanopes and deuteranopes is dependent on their differences in luminosity function. While the deuteranope matches red against yellow, the amount of yellow necessary in the match is considerably more than that required by the protanope who, due to the shortening of the red end of the spectrum matches/

matches a red against a much darker yellow. This is the simplest distinguishing feature, as both types match right across the red-green anomaloscope equation. The photopic luminosity curves of the dichromats corresponds with their similarly named counterparts among anomalous trichromats. The protanopes have a luminosity curve similar to the protanomalous i.e. shortened at the longer wavelengths, and the deuteranopes have luminosity curves similar to those of the deuteranomalous. Tritanopes have nearly normal luminosity curves.

In a most comprehensive study of luminous efficiency curves in congenital colour deficiencies, VERRIEST (1971) found no significant differences between a dichromatism and its corresponding anomalous trichromatism. All abnormal groups had mean curves which differed significantly from that of a comparable number of normals. This meant that both deuteranope and deuteranomalous did display a significant reverse Purkinjie effect in their luminosity curves which were only slightly below normal over the short wavelength end of the spectrum. (WRIGHT, 1952, did not consider the difference significant). The inter-individual spread within each colour defect was not any smaller than that within a group of normal observers.

3. Monochromats

This is the most serious anomaly of colour vision,/

vision, and was recognised as early as the 17th century. In terms of the matching experiment, any test stimulus can be matched by any one matching stimulus. The visual system is totally insensitive to colour per se, and only brightness differences are perceived.

There are two forms of monochromat, one the rod monochromat or typical achromat, and the other the cone monochromat or atypical achromat. The rod monochromat who supposedly has only rods and no cones in his retina, has a luminosity function in which the photopic curve is shifted to the normal scotopic curve (HILLEBRAND, 1889; MAY, 1907). In addition, visual acuity is poor and such individuals are photophobic. Frequently they show nystagmus. These factors are in keeping with the assumption that only rods are present in the retina. However, SLOAN (1954) found that dark adaptation studies in the fovea revealed a biphasic curve similar to that which occurs in peripheral regions in a normal eye. She concluded that two types of receptor were functioning, firstly normal rods, and secondly cones which have become photopic rods with a different light sensitivity to ordinary rods.

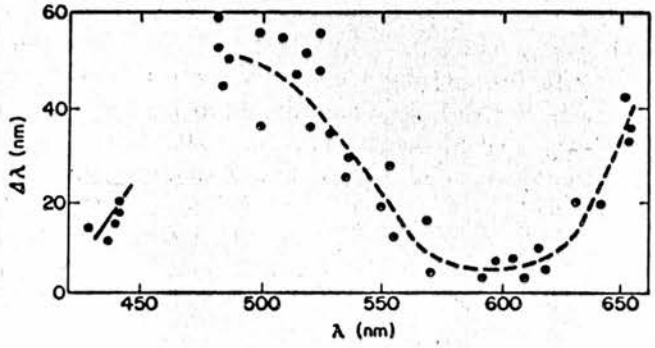
The cone monochromat or atypical achromat has a normal scotopic luminosity function but a photopic luminosity curve which is near normal peaking at 545 nm. (WEALE, 1953). The visual acuity is normal and there/

there is no photophobia nor nystagmus. Further varieties have been reported in which the luminosity function has a peak of 440 nm. at high luminance levels. (BLACKWELL's blue cone monochromats, 1957 1961). The biphasic nature of dark adaptation curves suggests normal rods and one cone system. There is no evidence of wavelength discrimination in either type of monochromat and it is presumed that while the rod monochromat sees all hues as grey, the cone monochromat sees them all of the same hue.

4. Experimental Dyschromatopsias

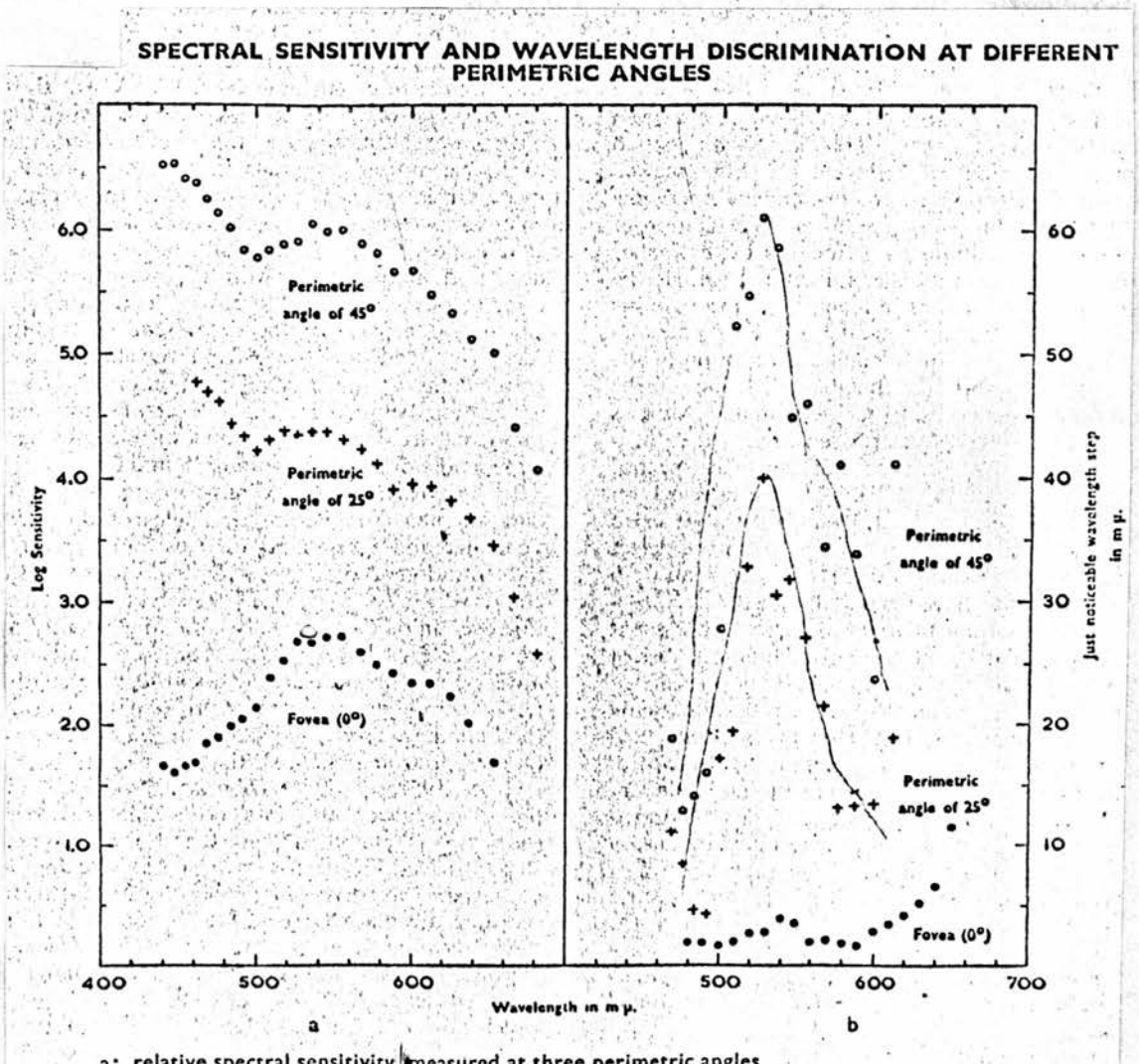
The use of certain experimental procedures introduces functional abnormalities in a normal eye. Three of these variations are considered briefly as indicating a departure from the normal trichromacy and linearity of vision.

In foveal viewing, if the visual field is made very small so that it is at most 20' of arc in diameter, normal colour vision becomes dichromatic (KONIG, 1896; WILLMER and WRIGHT, 1945). Furthermore, subjects who are dichromats may become monochromatic under these observational conditions (WILLMER, 1949). This evidence is based on matching experiments. In the case where the observational conditions are such that the normal trichromat performs as a dichromat, the matching stimuli which is absent is the one giving colour discrimination/



Wavelength discrimination step $\Delta\lambda$, plotted against the stimulus wavelength, λ, for discrimination using fields of diameter $<20'$. (*After Willmer and Wright* 1945.)

Figure 28



a: relative spectral sensitivity, measured at three perimetric angles
(The three sets of data are displaced vertically by arbitrary amounts to facilitate comparison.)

b: just noticeable wavelength step $\Delta\lambda$, measured at three perimetric angles

Figure 29

discrimination in the wavelength region 440 to 500 nm. Hence the visual performance is similar to that of the tritanope, and the term "small field tritanopia" is used to describe the effect. Fig. 28 shows the loss of wavelength discrimination under these conditions. It has been suggested that this phenomena could be due to the scarcity of blue sensitive cones (MARKS et al, 1964). (The ratio of red: green: blue cones has been estimated as 5: 5: 1 although these figures are questionable).

This dichromatism is not confined to central foveal regions. WRIGHT and THOMSON (1953) have shown that small parafoveal regions also exhibit this characteristic. In general, wavelength discrimination deteriorates rapidly if the stimulus is moved out into the peripheral retina. Data at three eccentricities are shown in Fig. 29 (after WEALE, 1953). MORELAND and CRUZ (1959), using a foveal matching stimulus to match a peripheral test stimulus, demonstrated that if the stimuli are not too small (test fields were 80' by 40' presented for 0.5 seconds duration) then three matching stimuli are required to match any test stimulus up to 25° from the fovea. At 30° eccentricity only two matching stimuli are required, and at 45° eccentricity nearly all wavelengths appear identical in colour. Colour vision, therefore, appears to change from being trichromatic, to dichromatic, to monochromatic as the/

the eccentricity is increased. The relation between the colour zones of the visual field and the receptor : bipolar : ganglion ratios have been mentioned as a possible explanation of peripheral colour vision (see page 37).

The obvious difference between the foveal and non foveal matches is the presence of rod participation in the latter. If the additional receptor system together with the cone systems had an independent informational channel, then vision would be tetra-chromatic in such regions. While this has been reported for particular observational conditions (BONGARD and SMIRNOV, 1956), extra-foveal vision is usually at most trivariant. Consequently, it is assumed that the four receptor classes pass their information into a three channel coding system.(For evidence of rod/cone linkage, see page 320). The additive nature of colour matches in these regions is dependent on the linearity of receptor responses. However, electro-physiological evidence indicates non-linear regions of receptor responses (TOMITA et al, 1967; ALPERN et al, 1970). Consequently, it is not surprising that the psychophysical data should indicate non-linearity. The non-linearity in vision is apparent at eccentricities of 10° so that extra foveal matches do not follow the additive rule (CLARKE, 1963). In addition to the peripheral rod responses, the colour vision of the/

the peripheral retina might be expected to be different from the foveal region not only because of receptoral or macular pigmentation considerations but also because of the higher degree of cortical convergence of peripheral pathways.

Finally, the variation in vision produced by adaptational conditions e.g. Bezold-Brücke effect must be mentioned. When an adaptation light is of very high luminance, colour matches which are established in the dark or at normal luminance levels break down (WRIGHT, 1936). A possible explanation proposed by BRINDLEY (1953) is that the inner layers of photopigment are normally screened by the outer layers. Intense bleaching of the photopigment reduces the screening and also decreases the optical density of the photopigment. Changes in optical density result in changes in spectral sensitivity and so account for the breakdown of colour matches. In the present context any colour matching will be carried out below such luminances so that this particular hue/luminance relationship will be avoided.

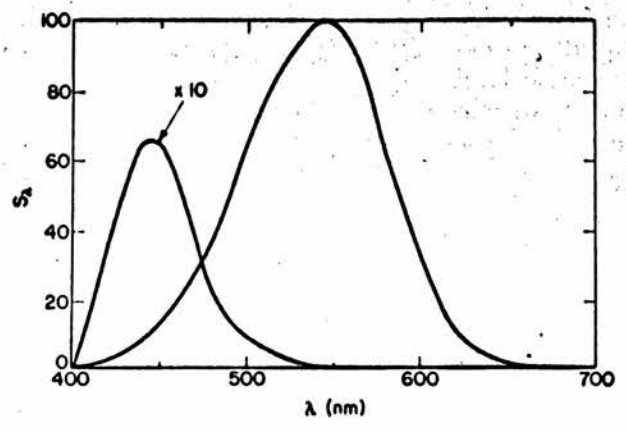
5. Physiological Basis

Physiological evidence on defective colour vision is of relatively recent origin and results mainly from the technique of fundus reflectometry. Firstly, however, it must be emphasised that the body of experimental data suggests three classes of spectral/

spectral response in cones. The absence of any receptor type would result in a decrease in the number of matching stimuli necessary in matching experiments, and hence result in defective colour vision. Similarily any neural scrambling of colour signals occuring after a normal quantal absorption by normal cones would result in defective colour vision. These alternatives are possibilities for both monochromatic and dichromatic vision and await experimental evidence. On the other hand anomalous trichromacy requires a change in one of the cone responses and can not arise solely from neural scrambling (RUDDOCK, 1971). Fundus reflectometry does not appear to be a sufficiently sensitive technique in anomalous trichromacy, and so the simplest assumption to date is that one of the three cone spectral functions is abnormal in any given anomaly - the red sensitive mechanism in protanomaly; the green in deuteranomaly; and the blue in tritanomaly. This assumption has indirect evidence from psychophysics (COLE and WATKINS, 1967; WATKINS, 1969 a.b.).

In monochromatic and dichromatic vision, fundus reflectometry has produced evidence to distinguish between the neural and photopigment theories. However, as no blue sensitive photopigment has been detected the evidence only relates to red-green forms of defective vision.

For dichromats, RUSHTON (1963, 1965), studying/



Relative spectral sensitivity function, S_λ, of the two protanope cone mechanisms—note that only a single-cone response is effective for $\lambda \geq 550$ nm.

Figure 30

studying cone pigments in deuteranopes and protanopes concluded that both forms of defective vision resulted from an absence of one of the normal photopigments. In protanopia the red pigment was missing and in deuteranopia the green pigment was missing. For the protanope, absence of the red sensitive pigment resulted in cone types with spectral sensitivity shown in Fig. 30. The green and blue sensitive pigments were the same as those in the normal eye. Absence of the red mechanism coincided with the constricted luminosity function of protanopes at long wavelengths. The lack of wavelength discrimination is explained as there is only one photopigment in the red green spectral range.

Deuteranopic vision is consistent with the absence of the green sensitive mechanism. However, the principle obstacle to this explanation has always been the near normality of the deuteranope's luminosity function. The fusion theories of dichromatic vision (see below) result from the difficulty in reconciling this apparent contradiction on a pigment absence basis. Rod monochromatic vision was consistent with the absence of normal functioning cone mechanisms. On the other hand in cone monochromacy there was evidence of different photopigments indicating that the neural scrambling hypothesis was a likely explanation for the loss of colour discrimination, WEALE, (1953b., 1959).

6. Incidence of Colour Defects/

6. Incidence of Colour Defects

The incidence of colour vision defects in a Caucasian population is approximately 8% of males and 0.6% of females. This sex difference is accounted for by the sex linked nature of colour vision defects. As the genes for these defects are carried on the X chromosome and are recessive, the defect is not exhibited in the presence of a normal colour vision gene. The male, with chromosome pattern XY, has a probability (p) of inheriting an X chromosome which contains a gene for defective colour vision from his mother. However a female, with chromosome pattern XX, must because of its recessive nature inherit two defective genes before a colour vision defect will be apparent. This condition requires one defective gene to be passed on from each parent. It follows that the probability of this occurrence is p^2, if the probabilities are considered as independent events. This is in accordance with the frequency of colour defects (males 8% to females 0.6%).

The probability of any particular type of congenital colour defect occurring in a population, (after NELSON 1938; KALMUS, 1965) is:-

Anomalous Trichromat	Deuteranomalous	.05
	Protanomalous	.01
	Tritanomalous	.0001 date unreliable
Dichromats	Deuteranope	.01/

Dichromats	Deuteranope	.01
	Protanope	.01
	Tritanope	$<$.0001
Monochromats	Typical (rod)	.003
	Atypical (cone)	.000001

7. Theories of Colour Vision

Long before physiological evidence had supported the notion of three differnet cone types, each with its own spectral response, the psychophysical evidence had pointed to the uniqueness of the number three in colour vision studies (see page 71). Its significance was first stressed by YOUNG, (1802) who suggested that colour vision was based on the presence of three different light sensitive organs. The idea, called the trichromatic theory of vision, was taken up and developed by HELMHOLTZ (1892). The theory, which was placed on a firm experimental foundation by MAXWELL (1890), who confirmed the trichromacy of colour vision, proposed that there were three sets of peripheral sensory mechanisms whose quantitative characteristics provided the basis for different types of colour discrimination. The three sensitivity curves corresponding to the three sensory mechanisms must be linearly related to the data from colour matching experiments - hence the many unsuccessful attempts to represent the luminosity curve by a linear combination of three hypothetical primary/

primary sensitivity functions (SHEPPARD, 1968).

Several theories exist with minor modifications, but as they are primarily based on the phenomena of colour mixing experiments they are called trichromatic theories and are classed with the YOUNG-HELMHOLTZ theory. In this group, explanations for dichromatic vision arose from either a loss of one of the fundamentals (KONIG type theories) or from a fusion of two fundamentals (AITKEN, LEBER, FICK type theories - see Graham, 1965, page 415). Consequently, in a König type theory, protanopia was due to a loss of the red process, and deuteranopia to a loss of the green process.

In fusion theories the two receptor types became identical in terms of quantal absorption but they maintained different central connections. Consequently, deuteranopia resulted from red light stimulating both central red and green systems when borh receptors contained red absorbing pigment, and protanopia resulted from green light stimulating both central red and green systems when both receptors contained the green absorbing pigment. The alternative approaches are supported by different colour vision phenomena, and no single approach satisfactorily explains all phenomena. It is possible of course that each alternative is correct so that protanopia is explained by a loss of one fundamental whilst deuteranopia is explained by the/

the fusion hypothesis.

There are a second major set of theories which are non-trichromatic and stem from the work of HERING (1878). These are known as the opponent pairs theories. Such theories came mainly from physiologists and psychologists, who had emphasised the subjective awareness of colour experience in contrast to the stimulus oriented trichromatic theories. There are four colours which appear to be unique: blue, green, yellow and red, and these are related to each other in a particular way to form three mutually antagonistic processes. The opposing sensations are red-green, yellow-blue, and black-white, the equal stimulation of any pair producing the achromatic neutral sensation. For Hering, colour phenomena were not only to be explained in an analysis of the stimulus but also by the characteristics of the visual mechanism. Hue shifts with luminance changes BEZOLDE-BRÜCKE effect, and simultaneous contrast effects are examples of phenomena which lend themselves to an opponent pairs theory. While these phenomena remained primarily subjective, it was difficult for early theorists to give experimental backing to their ideas. The first quantitative formulation of an opponent pair theory resulted from the work of HURVICH and JAMESON (1955).

Early controversy over the two principal types of theory, trichromatic and opponent pairs, has subsided/

subsided to reach a compromise position (GALIFRET, 1960). The resulting "zone theory" has trichromatic features at the photoreceptor level in its postulation of three cone types and opponent pairs' features at subsequent stages in keeping with evidence from the work of MARKS et al, (1964); SVAETICHIN and MacNICHOL (1958); DE VALOIS, (1960) (See page 52) Alternative types of zone theory first propounded by VON KRIES (1905) are WALRAVEN'S, (1966) and JUDD'S, (1958).

8. Classification of Colour Defects

The terminology used in the classification system outlined above is probably the most widespread and popular amongst English speaking countries. There is, however, a further system proposed by VON KRIES (1924), which is particularly appropriate when dealing with acquired dyschromatopsias and is also applicable to the congenital defects. It consists of three systems called absorption, alteration and reduction, which implicate the area of impairment in the visual system.

The absorption system is characterised by the normality of retinal mechanisms but by an impairment of colour vision due to prereceptoral factors (e.g. cornea or lens). This impairment can be eliminated by appropriate readaptation to the incident light. An/

An absorption system is non-selective if the modification of the retinal illumination is the same for all monochromatic radiations of the visible spectrum. It is selective if this modification varies with wavelength. In a selective system the luminosity function is distorted, and colour equations are altered.

In contrast the alteration systems and reduction systems are attributed to anomalies in the retinal mechanisms. The alteration system is similar in effect to the performance of anomalous trichromats. It is characterised by the non-acceptance of certain normal colour matches. The implication is that one or more of the fundamental curves are distorted, so that no linear combination of three normal curves can account for the colour vision performance. The reduction system is one in which normal colour matches are accepted, but in addition many non-normal matches are acceptable including those of the anomalous trichromat. The term is usually reserved for a type of dichromatism in which two fundamental response curves are implied instead of the usual three. Because the normal colour matches are accepted the system is seen as a collapse of the normal system.

Whichever classification system is used, care must be taken over the implications of the system. On the trichromatic theory, it might be thought that the loss of one fundamental curve implied that an individual was/

was red blind, green blind or blue blind. However, the reported sensations of such subjects do not fit such a nomenclature. For instance - a so called "red blind" individual does not simply not see red. The confusion lines of the dichromat indicate that there are several colours which are seen in the red region of colour space and several which are confused in the blue or green colour space regions (See Fig. 26). And yet this type of observable colour confusion is still compatible with the absence of the red photopigment. Again if Hering's terminology is used, the colour vision defects are grouped so that colour defects are classed as red-green or yellow-blue confusions. These problems are particularly important in the classification of acquired dyschromatopsias (See page 105).

Although until recently congenital colour vision defects were frequently quoted as being the only forms of defective colour vision there is now widespread acceptance of acquired colour vision defects as an entity in themselves (see introduction). While the congenital defects have no implied morbidity and are stable, the acquired defects can be attributed to a pathological basis, or to normal ageing processes, or to a by-product of some systemic disease.

b.) Acquired Dyschromatopsias

1. Clinical/

1. Clinical

This category is reserved for colour vision defects which have developed from a state when the subject's colour vision was normal. The change over time is one of the principle characteristics of this type of anomaly. It might arise from pathological disturbances in the visual system, physiological imbalances, or injuries. It can be unilateral, in contrast with most congenital defects which are nearly always bilateral. For a comparison of congenital and acquired dyschromatopsias see page 115.

The original studies on acquired dyschromatopsias were made in the nineteenth century (BENEDICT, 1864; MAUTHNER, 1881) culminating in the German school comprising Helmholtz, Koenig, Von Kries, Koellner, Simon, Nagel. KOELLNER (1912) summarised the work of this German period and it is his name which subsequently was given to the "rules" which were formulated. It is these contributions which first demonstrated ways in which diseases of the eye could influence colour perception.

The change of disease with time underlines the basic instability of acquired dyschromatopsias. While the congenital defects form fairly distinct well-defined groups, the acquired defects occupy a continuum extending from nearly normal vision to blindness. Nevertheless attempts to break the continuum into recognisable/

recognisable categories or stages have been made. For instance, classification on the basis of the trichromatic theory rests on the number of primaries required to match a test stimulus. Different combinations of three, two and one matching stimuli can be found so that the stages can be divided into trichromatic (whether normal or abnormal), dichromatic, and monochromatic. One problem with this approach, is that the acquired defect unlike the congenital defect is particularly dependent on the substense of the stimulus, and can frequently improve if the stimulus area is increased. Thus the classification of a defect depends on specific stimulus properties in the test situation. A more general problem associated with this approach is the use of terminology developed from theoretical ideas about congenital defects. Unfortunately, the carry over of terminology from the congenital to the acquired field brings with it implications about the cause of the acquired defect. Such inferences are without foundation. The use of this terminology, is in fact no more than a description of the behaviour of the acquired defect in terms of the behaviour of the congenital defect. Consequently, when for example acquired defects have reached a "dichromatic" stage and simulate deuteranopia, it should not be inferred that the mechanism of the defect is comparable to the defective mechanism in the congenital deuteranope. It is only the test performance/

performance which justifies the comparison. However, with these reservations, this behavioural description is useful and in the following passages it is frequently interchanged with an opponent pairs terminology.

It is more common to find the classification of acquired dyschromatopsias based on the principal types of colour confusion and on modifications to the spectral curve of luminous efficiency. This terminology is in keeping with HERING (1920) and VON KRIES (1924) rather than with the trichromatic theory. Workers in the German period discovered eye diseases which modified the light transmitted to the eye by the refracting media, resulting in particular losses at the blue end of the spectrum. Von Kries himself demonstrated the essential difference between the absorption systems and the alteration systems which were the congenital trichromatic anomalies. However, it is the work of BULL (1883) and KOELLNER, (1912, 1929) who differentiated between acquired defects of the red-green axis, acquired defects of the yellow-blue axis, and acquired defects with no apparent axis. The acquired dyschromatopsia of the red-green axis was observed in all diseases of the optic nerve. It was similar in type to the congenital deuteranopic defect in its colour confusion and the position of the spectral neutral point. In addition, the photopic curve of luminous efficiency was normal. The acquired dyschromatopsia of the yellow-blue axis/

axis was found in all conditions associated with the refracting media or the retina. It was similar in type to the congenital tritanope in its colour confusions and in the position of the spectral neutral point. However, unlike the congenital tritanope, who has a nearly normal luminosity curve, this acquired defect was associated with a depression of the photopic luminosity curve towards the blue end of the spectrum. Both the red-green and the yellow-blue types were thought to develop from a trichromatic phase so that it was possible for them to pass through the dichromatic phase to the monochromatic stage. The acquired dyschromatopsia without apparent axis was found to be associated with certain conditions of the optic tract. Unlike the congenital achromatopsia, its luminosity curve was almost normal and showed no shift towards the scotopic curve.

These represent the general findings of the German school. The association of red-green defects with lesions in the inner retinal layers and optic nerve, and yellow-blue defects with lesions in the outer retinal layers became known as KOELLNER'S Rule (1912).

Little progress was made until the 1950's when interest in acquired dyschromatopsias was revived. The principal workers in this period were Jaeger, Gruetzner, Zanen, Dubois-Poulsen, Hong, Ohta, Cox, Wright, Francois, Verriest. Many of the earlier findings of the German/

German school were confirmed by the later workers together with several additional findings. One of the most interesting of the new discoveries was the division of the acquired red-green defects into two principal types, one of which maintained the features noted by Koellner, while the other, (found in juvenile macular degeneration), was accompanied by a shift in the photopic luminosity curve. This shift was progressively towards the blue end of the spectrum until it finally coincided with the scotopic luminosity curve. (COX, 1960; GRUETZNER, 1961; VERRIEST, 1963). The new type of red-green defect was called Type I and the previous type recognised by Koellner, Type II.

Conclusions resulting from the more recent researchers can be summarised as follows:-

Acquired Dyschromatopsia of Red-Green axis - Type I

The photopic visual system is principally affected. The normal anomaloscopic equations are no longer accepted, and in the red-green equation there is a shift in the mid-matching point towards the red in the early stages of this defect. In the later stages the defect progresses so that further colour discrimination is lost. All mixture ratios are accepted as matching a standard, and the defect resembles that of the typical achromat. The progressive degenerative change has been named as a process of scotopisation (VERRIEST, 1963). This name is particularly associated with the/

the changes which take place in the photopic luminosity curve. There is a progressive shift of this curve towards the short wavelengths, so that in its final stage the luminosity curve coincides with the scotopic curve. The progressive changes in colour discrimination are from trichromatic, to dichromatic, to monochromatic. In the dichromatic stage the wavelength discrimination is similar to the protan and deutan. In the monochromatic phase vision is similar to the typical achromat with associated reduced visual acuity and photophobia.

Acquired Dyschromatopsia of Red-Green axis - Type II

This defect is first demonstrated on the anomaloscope by a shift in the red-green equation towards the green, the normal colour matches being no longer accepted. In the later stages the defect resembles that of the deuteranope in that several red-green mixtures are accepted as matching a standard yellow. The progression of this defect passes from a trichromatic stage through a dichromatic stage, and finally to an achromatopsia. In the trichromatic stage all coloured stimuli are desaturated. This remains the case in the dichromatic stage as there exist losses in colour discrimination at right angles to the main deuteranopic confusion lines. VERRIEST (1964), refers to these colour losses as confusion zones. However, the deuteranopic losses are predominant with a spectral/

spectral neutral point around 500 nm. Wavelength discrimination data is also of the deutan type. Other spectral neutral points have been discovered around 570 nm. (GRUETZNER, KIESLICH and WEIL, 1961). The photopic luminosity curve is normal apart from some atypical cases reported by COX (1960, 1961). This is in contrast with the Type I dyschromatopsia. The colour naming of all the acquired groups is generally good because as the visual system was once normal, the association of words with visual input was firmly established before a deterioration took place. This is in contrast to the colour naming of a congenital defective which is often (particularly in dichromats) quite unreliable. In the acquired defective the initial attachment of words to colours is a good basis for noting subsequent observable changes in the description of colours. VERRIEST, (1964) has described in detail the colour naming of patients with an acquired dyschromatopsia as the vision progressively deteriorates. In the dyschromatopsia of the red-green type, the principle feature of colour naming in the trichromatic phase, is that the blue-greens are called pale greens and that the yellow/greens are called pale yellows. Blues and yellows are both named correctly. The longer wavelengths undergo a wavelength shift so that oranges are called yellows, and reds either red or orange. In the dichromatic stage the blues are still named as blue, and the yellows/

yellows and oranges as yellow. Greens and yellows are named as yellow but blue-greens are seen as colourless as the spectral neutral point falls in this wavelength region. Reds may be seen as reds, yellows, or even colourless if a second neutral point is present. As the monochromatic phase is approached, blue is the only colour to be correctly recognised.

Acquired Dyschromatopsia of the Yellow-Blue axis

This acquired tritanopic colour vision defect follows both red-green types in undergoing progressive degeneration from a trichromatic through a dichromatic stage to eventual achromatopsia. In the trichromatic stage it is principally the perception of blues that is affected. This includes blue-greens, violets and purples. The dichromatic phase is characterised by confusion lines of the tritanopic or tetartanopic type (See Fig. 26), so that two spectral neutral zones are found, one at about 465 nm. and the other at around 550 nm. Wavelength discrimination curves are of the tritanomalous and tritanopic type. Of great importance is the fact that in addition to the yellow-blue type of loss, there is now a concomitant defect on the red-green equation, with in particular a displacement of the mid-matching point to the red end of the spectrum. When this stage is reached, normally matching red-green mixture ratios are no longer acceptable. This red-green defect adds individual variation to the predominant/

predominant yellow-blue defects and has a particular effect on confusion zones and spectral neutral points. Further deficiencies in absorption systems also add to the individual variations.

The monochromatic phase is reached by a process of scotopisation. Workers in the German school had concluded that the photopic luminosity curve in this defect was depressed at short wavelengths. However, more recently HONG (1957), COX, (1960, 1961), GRUETZNER, (1962 a.b.), VERRIEST, (1964) have all shown that this is not the case. Instead the depression is at long wavelengths so that the normal luminosity curve undergoes a progressive shift as in the Type I red-green defect towards the blues, terminating in the scotopic luminosity curve.

Colour naming is again of interest. In the trichromatic stage all colours are named correctly with the exception of the blues. In its dichromatic stage, violets, blues and blue-greens are seen as colourless in accordance with the spectral neutral zone. Similarly in cases where a second neutral point exists, the yellows are seen as colourless, as reds, or as blues. In the dichromatic stage colours at right angles to tritanopic confusion lines represent the general dimension of colour perception. Longer wavelengths are called red, which is finally the only colour correctly recognised as the defect progresses/

progresses to achromatopsia.

Acquired Dyschromatopsia without apparent axis

The general conclusion of the later workers was that this defect was not representative of a single entity, but instead was characteristic of a stage of any of the former defects. It was recognised by a general loss of colour discrimination.

If a point of colour space is selected, the defect results in an enlargement of the MacAdam ellipses rather than a selective loss (See Fig. 27). This can be produced by a defect of a red-green type in conjunction with a defect of the yellow-blue type. Its monochromatic stage can result from any of the other types of progressive change. When this final stage of acquired achromatopsia has been reached, it is the photopic luminosity curve which gives an indication of the original type of colour loss. For instance if the photopic luminosity curve is normal, then the achromatopsia results from the Type II acquired defect of the red-green axis. If it is abnormal then it is likely that this defect has started as a Type I defect of the red-green axis.

These are the general characteristics and types of acquired dyschromatopsia recognised by the later research workers. The following comparisons can be drawn between the acquired and the congenital dyschromatopsias:-/

dyschromatopsias:-

1. The acquired dyschromatopsia is unstable and can change markedly over time. Congenital defects are stable and only undergo relatively minor changes in the normal ageing process.
2. The acquired defect depends on pathology, and will mirror the pathological change either in improvement or deterioration.
3. Unlike the usual bilateral congenital colour defect the acquired defect can exist in one eye or in one part of the visual field. Its severity can vary from one location to the next. Consequently, an increase in stimulus area is generally accompanied by an improvement in vision. The acquired defect is also sensitive to other changes in the stimulus parameters. Adaptational conditions, luminance, and stimulus presentation time, can all influence the degree of visual loss.
4. In a unilateral defect it is possible to compare colour sensations of a normal and affected eye. This enables a good description of visual losses to take place. Colour naming of the congenital defective is unreliable.
5. Acquired dyschromatopsias are frequently accompanied by alteration in other visual functions, i.e. in acuity, fusion frequency, and light and dark adaptation./

adaptation.

6. The behaviour of acquired colour defects resembles the behaviour of congenital defects. The CIE chromaticity diagram can be used to indicate both the extent of visual loss and the confusion lines. Because of the wide variations in pathology there are correspondingly wide variations in function. These individual differences are much greater than those within the congenital categories. Confusion lines can become confusion zones showing an overall degeneration rather than an axial one.

Further observations concerning acquired dyschromatopsias are as follows. The colour naming data are non quantifiable, and of type B3 in the general scheme of psychophysical evidence (see page 67). Their possible role in acquired dyschromatopsia can be seen as a guide to the various types of acquired defect. However, further changes in colour naming can occur from absorption systems which occur from prereceptoral sources. For example the refracting media can give abnormal diffraction or refraction of light, and blood exudates can provide obstacles to light transmission. Anomaloscopic equations can be altered by such processes and the luminosity curve can be affected. Colours may appear desaturated and in certain instances (e.g. nuclear cataract), the vision becomes dichromatic/

dichromatic (VERRIEST, 1963). Verriest discovered that the majority of the absorption systems did give rise to predominantly yellow-blue type losses with correspondingly slight variations in the luminosity function.

A further variety of colour vision phenomena which is applicable to the absorption system have been named as chromatopsias by DUKE ELDER, (1946). These are instances where the patients perception of a coloured stimuli is different from that normally associated with the stimulus.

Duke Elder's terminology is:-

Ianthinopsia	for	the	case	of	abnormal violet vision
cyanopsia	"	"	"	blue	"
chloropsia	"	"	"	green	"
xanthopsia	"	"	"	yellow	"
erythropsia	"	"	"	red	"

Other instances of faulty colour naming which are outside the scope of this project exist. Cortical pathologies leading to word blindness, demonstrate the inability of colour naming in instances where colourimetric equations remain normal.

More specific background information on functional changes which is relevant to specific clinical populations is given in the appropriate results section.

2. Ageing/

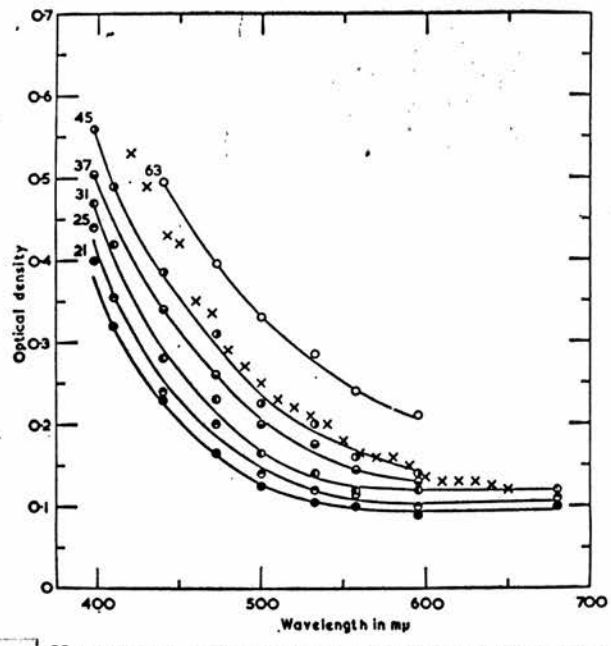


Figure 31

—YELLOWING OF THE HUMAN CRYSTALLINE LENS WITH AGE.

Ordinate, density; abscissa, wavelength. The numbers indicate age in years. Circles, measurements for the living eye; crosses, for an excised lens (F. S. Said and R. A. Weale).

2. Ageing

The acquired dyschromatopsias of Section IVb 1 are mainly associated with pathological conditions. The visual losses to be considered in this section are due to physiological changes which occur in the ageing process. The extent to which age changes are detectable in vision, depends on the nature and sensitivity of the test of visual function employed. It is appropriate, therefore, to quantify age changes for each of the tests used in this report. In the following section in which the development of tests is described, norms will be given for different age groups so that control groups exist for individuals of all ages in the clinical experimental groups. For present puposes, age changes in vision are discussed in a general context as they form an important group of acquired dyschromatopsias. Examples of typical changes are related to possible causal factors.

(i) Possible Factors

In general, studies of the age continuum have shown that there is a growth of visual function up to 20 years and decline from 30 years onwards (WRIGHT 1946; LAKOWSKI, 1958; LAKOWSKI and ASPINALL, 1969; STILES and BIRCH, 1959). The reason for the age change is still unclear, although certain contributory factors have been isolated. Some changes in colour vision can be clearly seen to be related to the lens (Fig. 31),/

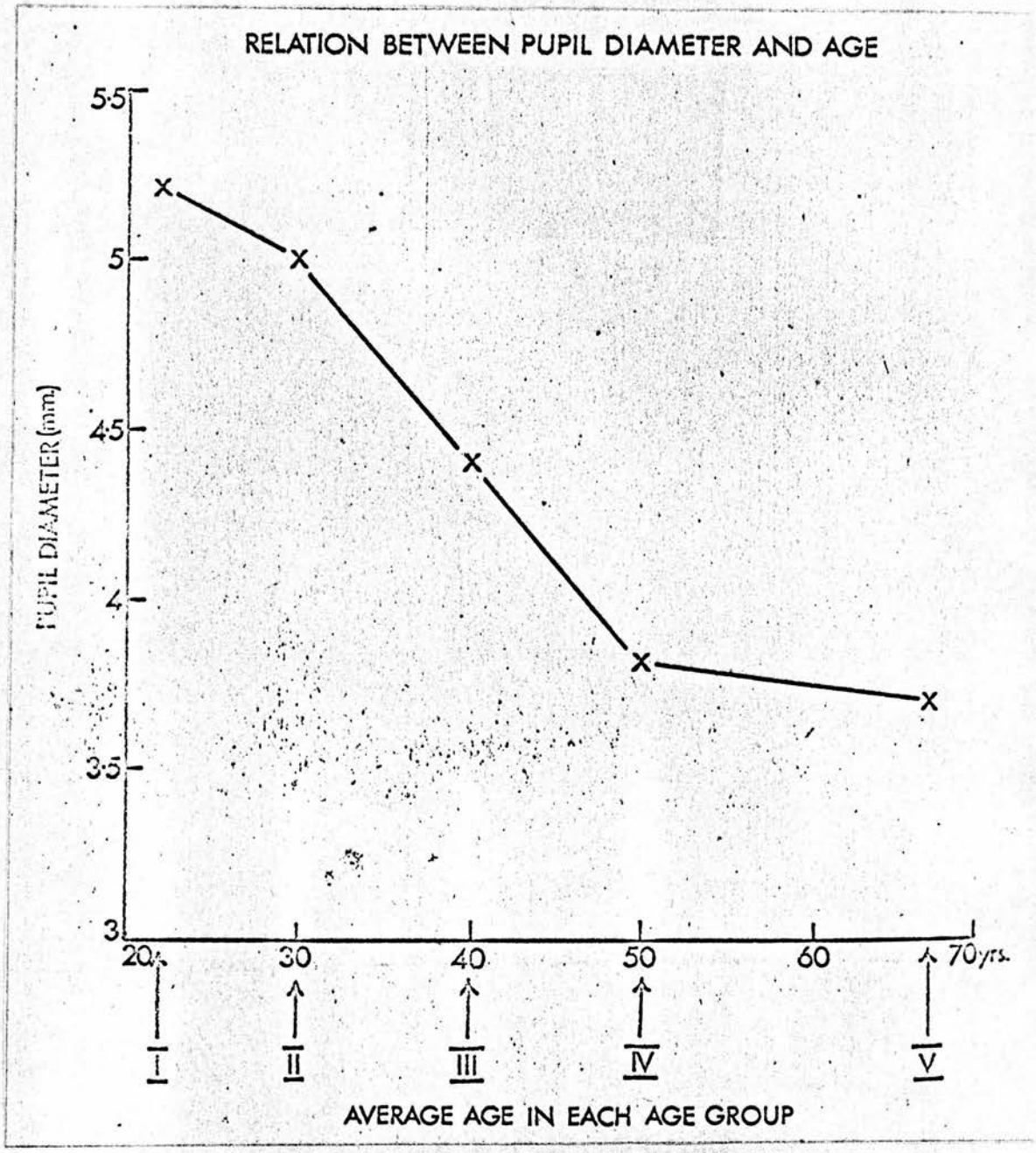
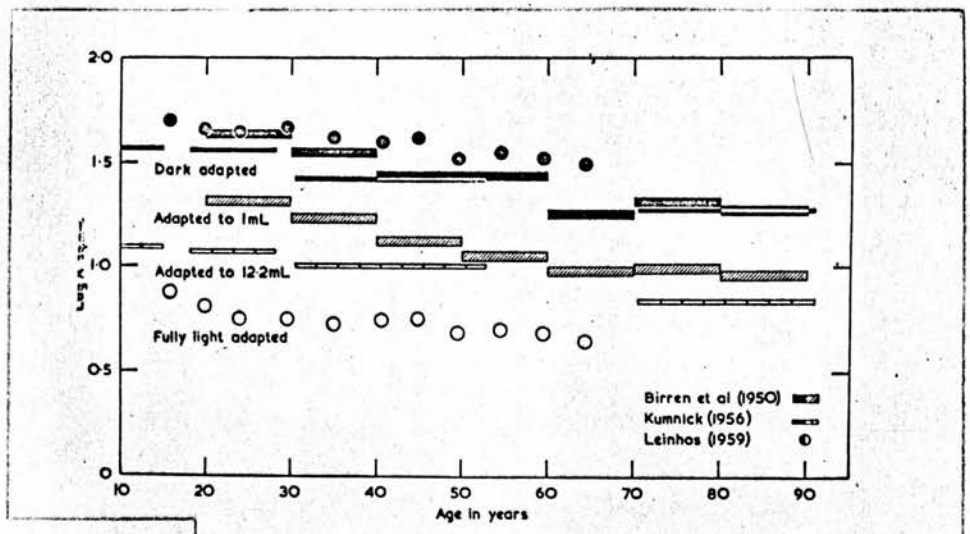

RELATION BETWEEN PUPIL DIAMETER AND AGE
PUPIL DIAMETER (mm)
5·5
5
4·5
4
3·5
3
20
30
40
50
60
70 yrs.
I
II
III
IV
V
AVERAGE AGE IN EACH AGE GROUP

Figure 32



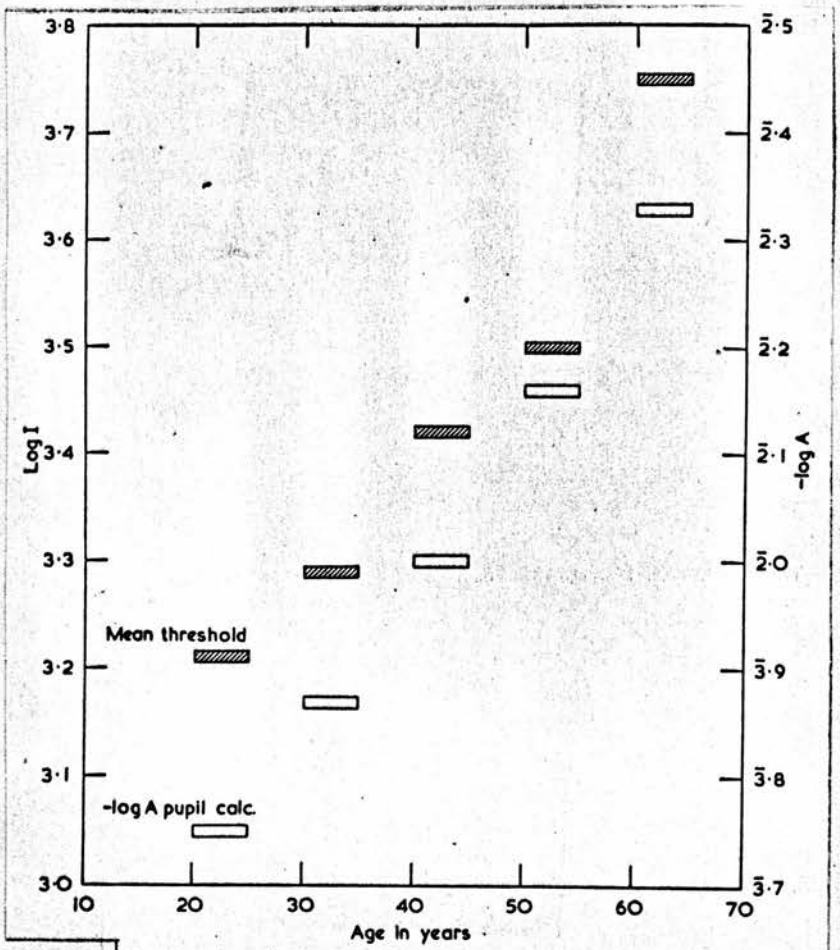
The senile variation of pupillary area and its dependence on the level of adaptation

Figure 33

(Fig. 31), which yellows with age and so absorbs more and more of the short wavelengths as age increases (WALD, 1949; SAID and WEALE, 1959) WEALE, 1963). Other age effects are related to the retinal illumination level.

The amount of light falling on the retina is governed by pupil size (SLOAN, 1940). Pupil size, therefore, is of considerable importance in studying retinal sensitivity, as variations in the amount of light falling on the receptors will affect threshold values. An investigation by BIRREN, CASPERSON and BOTWINICK (1950) showed that there was considerable reduction in the size of the pupil with increasing age. In a sample of 222 subjects ranging in age from 20 to 89 years, the differences in pupil diameter ranged from 5.1 mm. (mean of 20-29 year old group) to 3.4 mm. (mean of 80-89 year old group). Furthermore the authors found that there was not a linear relationship between pupil size and age as PHILLIPS, (1939) and SLOAN (1940) had assumed. Typical results of the pupil size/ age relationship are shown in Fig. 32 at an adaptation of 31.5 abs. (Standard Goldmann Perimetric conditions); Fig. 33, after WEALE, (1963) illustrates the relationship under different adaptational conditions.

As the pupil area constricts with age, less light falls on the older retinas. The influence of this effect on the absolute threshold to white light can be/

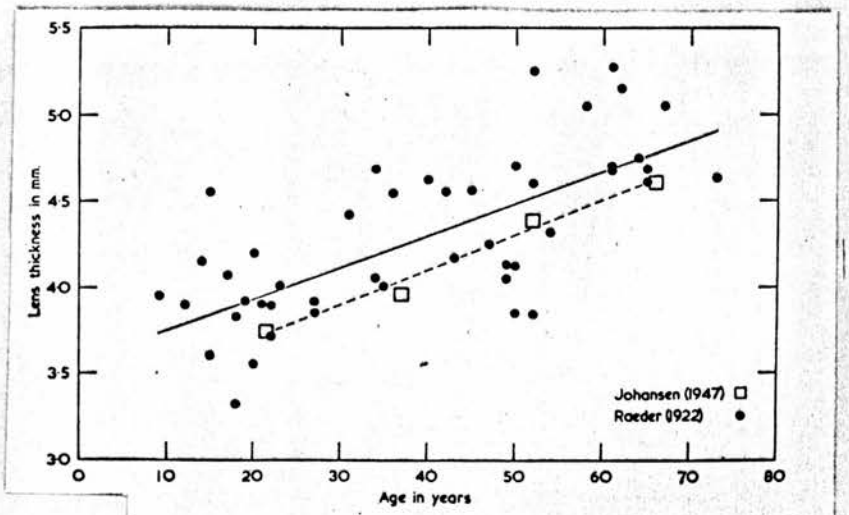


Absolute threshold and pupil area are approximately inversely proportional to each other (after Robertson and Yudkin, 1944)

Figure 34

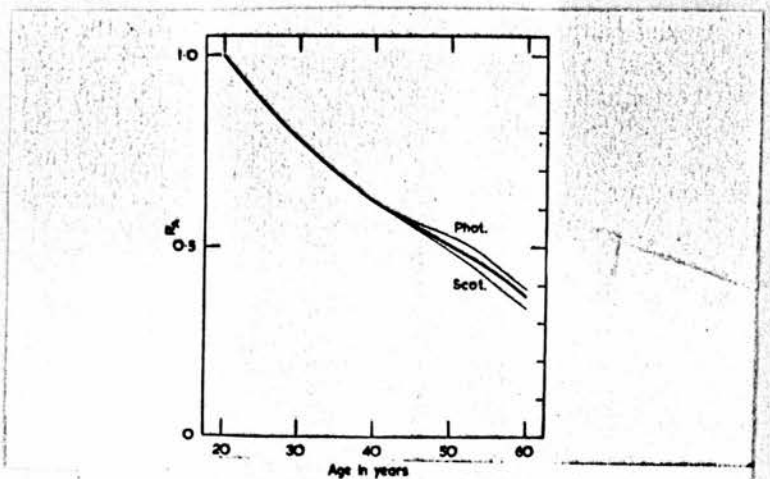
be seen in Fig. 34. It appears that the pupil constriction is sufficient to account for the threshold changes, at least as far as the absolute threshold is concerned. While older subjects might do worse on visual tests because of the decrease in light entering the eye, a smaller pupil may have its advantages (FERREE, RAND and LEWIS, 1935). The effect of light scattering caused by opacities in the eye will be less in small pupils than in larger ones. In addition, defects in refraction become of less importance if the size of the aperture is reduced. However, the over-riding influence in the determination of retinal sensitivity is the reduction in the amount of light falling on the retina and this, most authors agree, occurs with increasing age.

Two further factors are in operation which tend in fact to compensate for each other. Firstly the shape of the lens, with more light absorbing material in its central part than at its edges, produces differential absorption in a central and peripheral beam. The central ray undergoes greater absorption than the peripheral ray. If the pupil size is reduced, all light entering the eye necessarily passes through the thicker part of the lens, and consequently less light reaches the retina. On the other hand the Stiles-Crawford effect, showing that a central ray is subjectively brighter than an equivalent peripheral ray,/



The variation of the depth of the anterior chamber (top) and of the sagittal thickness of the lens (bottom)

Figure 35



The relative amounts of effective light reaching the light-adapted (Phot.) or dark-adapted (Scot.) retina at various ages between 20 and 60 years (Weale, 1961*b*)

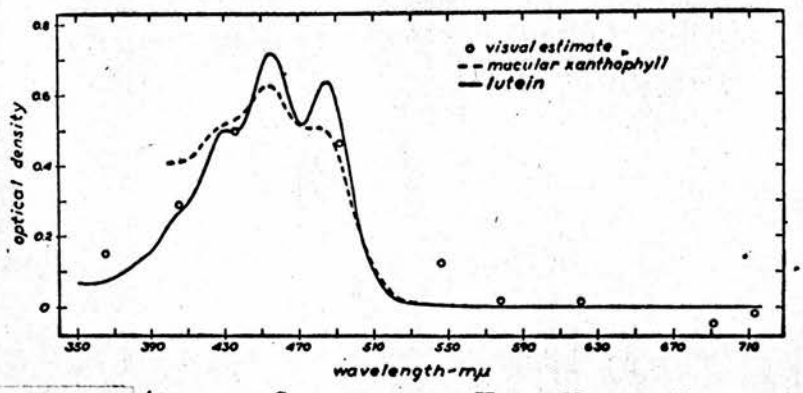
Figure 36

ray, will work in opposition to a reduction in sensitivity brought about by the increased absorption of the central ray. As yet there is no data in the literature on the relationship between the Stiles-Crawford effect and age.

Further variations in dimensions and mass of the lens are shown in Fig. 35. Again the older person is seeing through an optically denser filter, with a corresponding reduction in visual sensitivity. This effect is amplified by the process of nuclear sclerosis in which the central part of the lens becomes progressively more dense with age.

A most comprehensive account of the age effects on the optical property of the eye is given by WEALE (1963). The variation in the effective amount of light reaching the eye with age is shown in Fig. 36, for both photopic and scotopic conditions. The similarity of the photopic and scotopic curves can be accounted for by two processes. In the first place the yellowing of the lens with age reduces the effectiveness of blue light and so is particularly detrimental to the scotopic system. On the other hand the constriction of pupil diameter in the photopic state allows less light into the eye, and furthermore only permits light to enter through the central lens regions which are optically denser than the outer regions (WEALE, 1961).

In addition to the alteration in spectral energy/



-Absorption Spectrum of the Human Macular Pigment.

The visual estimate was obtained by a comparison of the sensitivities of peripheral and foveal cones (G. Wald).

Figure 37

energy reaching the receptors, which results from passage of light through the lens, there is a second filter of considerable importance over the central retina. This is the macula lutea or macula pigmentation. Its transmission characteristics are shown in Fig. 37 after WALD (1949). The general effect of the pigment is to absorb the short wavelengths. In addition individual differences in pigment concentration will alter the colour equations accordingly. There is no reliable evidence as to whether this pigment changes its optical density with increasing age as does the lens. WEALE (1963) considered it probable that the macula pigment did become yellow with age. However, he thought it unlikely that the rate of change was similar to that of the lens as the retina, with its superior blood supply, had more chance of moving ions to and from the macula. The transmission characteristics of the macular pigment are also quite different to estimates given for the lens (Compare Fig. 31 and Fig. 37). Although the role the macular pigment plays in vision is uncertain, an attempt to estimate its effect on a specific colour vision test situation was made by ASPINALL (1967). Details of this are given in the development of test section.

Finally WEALE (1961) considered the change in the cornea with age to be a second order effect, and together with the aqueous humour and the vitreous/

vitreous humour, unlikely to have much photometric significance. Consequently, he suggested that a consideration of the age variation in retinal illumination should be confined to changes in the lens and pupil only. His results showed that in general the retinal illumination at the age of 60 was about one third of its value at the age of 20.

In addition to macular pigment changes, other changes at the retinal level may exist and have a bearing on retinal function. Weale considered the evidence to be inconclusive and that the decrease in retinal function could be due to prereceptoral factors already mentioned. On the other hand, LAKOWSKI (1969) thought that the more extensive losses in visual function with age could be due to the fact that after 30 years there was an increasing number of people with minor pathological changes in addition to normal age changes. Many latent clinical conditions could be present in a covert state, so as to accelerate the senile degenerative process. Consequently at 50 years it was very difficult to define a "normal population" and normal senile changes. It will be shown in the results section that many pathological conditions give rise to colour vision losses which are similar to those of the old, and resemble an early ageing effect. Consequently, in these circumstances a normal ageing process can be aggravated or accelerated./

accelerated.

(ii) Effects on Colour Vision

In studies of the age effects on colour vision, research workers have used many different tests to observe the age changes. It is apparent that the changes observed are critically dependent upon the construction of the test used. Consequently tests which are devised to detect congenital red-green defects are unlikely to show age changes if the effect of age changes is principally in the short wavelength region. In a similar way the extent of the age change also depends upon the sensitivity and nature of the test.

In studies using the pseudo-isochromatic plates, (e.g. the Ishihara Test) few significant differences with age have been measured. TIFFIN and KUHN (1942), and SMITH, (1942) described age changes in colour discrimination. However, BOICE, TINKER and PATERSON, (1948) using the Ishihara on 236 subjects and CHAPANIS, (1948, 1950) testing 574 subjects on the Ishihara and Dvorine plates found no correlations with age. On the other hand differential threshold tests, using hue, saturation, or luminance as variable, indicated minimal thresholds between 20 and 30 years and a subsequent decline in the blue, violet and blue-green thresholds. (HESS, 1909; PIERCE, 1934; GILBERT, 1957; BIRCH-COX and WRIGHT, 1961; OHTA, 1961; VERRIEST, 1963; LAKOWSKI, 1958). In addition OBI (1954) and BOLES CARENINI (1954)/

(1954) demonstrated a shift in the mid-matching point on the red-green equation towards the green, but this shift only became significant after age 60. (This slight shift is unlikely to be picked up on a coarser test of red-green vision such as the Ishihara). Conversely LAKOWSKI (1958) found significant shifts in mid-matching point towards the red in three age groups from 5 to 25 years. After the age of 25, the mixture ratio remained static. However, shifts at the long wavelengths were small in comparison to the reductions in sensitivity at short wavelengths. In fact, VERRIEST (1963) found that the lower limit of the visible spectrum was 300 - 314 nm. up to 34 years; 315 - 350 nm. between 34 and 43 years; 350 - 393 nm. between 43 and 67 years and over 400 nm. in subjects over 67 years of age. (Paradoxically DODT and WALTHEN, 1958, have shown an increased sensitivity to ultra violet in the aged which is thought to be due to increased fluorescence of the lens in nuclear sclerosis).

WRIGHT, (1948) investigated the variability in locating white in the CIE space among subjects of different ages. The variations were aligned in a particular direction and thought by Wright to be due to variations in macular pigment concentration only, as the dominant wavelength of the pigment coincided with the dominant wavelength of the alignment. This evidence suggested that the macular pigment did vary in/

in concentration with age and was the cause of individual variations in colour vision. A similar shift was shown by JUDD, PLAZA and FARNSWORTH, (1950) with an additional curve towards the red end of the spectrum. This was supposedly due to lens colouration in accordance with the data of SAID and WEALE (1959).

It is apparent from the evidence already cited that while age changes are seen to take place by many authors, there is much less agreement on the role of the contributory factors producing age losses. For instance it is possible that measurable age changes in function can be reversed if the illumination level in the test is increased for the old (WESTON, 1949). However, the problem of whether the prereceptoral changes with age (principally pupil diameter changes resulting in reduced retinal illumination and lens changes resulting in the selective absorption of short wavelengths), are a sufficient condition to explain age changes, is one which has been central to studies of age effects. It is interesting to note that two of the recent major studies on age and colour vision came to different conclusions.

Firstly, LAKOWSKI (1962), using the PICKFORD-NICHOLSON anomaloscope to study age changes included a group of aphakics, and showed that the disturbance to colour could be partially cancelled by extraction of the crystalline lens. However, the improvement/

improvement in vision was only partially complete and never achieved the fine discrimination present in the 20-30 year age group. In those aphakics with heavy pigmentation changes or minor pathologies, no improvement occurred upon removing the lens, and their performance remained worse than that of a comparable age group. This evidence received support from a different approach to the problem. In an attempt to simulate age changes in young healthy eyes, Lakowski used yellow filters with different transmission characteristics. The optical density of these filters in conjunction with the macular pigment data of WALD (1949) was calculated, and compared with estimates of lens densities from the data of SAID and WEALE (1959) in conjunction with the macular pigment data of Wald. Lakowski found that the breakdown in colour vision was not as great in this experimental group as it was in the aged subject. Thus other factors need to be invoked to account for the observed age changes. VERRIEST (1963), came to the same conclusion using the Farnsworth Munsell 100 hue test.

The second major study was carried out by RUDDOCK (1965) using the Wright trichromatic colourimeter. Both the Verriest study using surface colours, and the Lakowski study with the Pickford anomaloscope used colours consisting of many wavelengths. This necessarily occurs in surface colour and the anomaloscope was deliberately designed to be a simple optical instrument/

instrument with broad band filters. On the other hand the Wright colourimeter has the facility of monochromatic light and is consequently a complex optical instrument. The importance of monochromatic stimuli in this context is that the interposition of any filter, no matter what its transmission characteristics, has only the effect of reducing the intensity of a monochromatic beam. Consequently if the equality of brightness is maintained between the two photometric fields, the matching range and mixture ratio should be unaffected by prereceptoral absorption. (WRIGHT (1946) demonstrated that the relative luminances of monochromatic matching stimuli and their chromaticity co-ordinates were independent of prereceptoral absorption. Furthermore BEDFORD and WYSZECKI (1958), found wavelength discrimination to be almost independent of luminance level over a range of intensities including that of 100 trolands at which discrimination was carried out in RUDDOCK's study). By use of this instrument RUDDOCK had, therefore, eliminated the effect of an ageing lens or of macular pigment variations.

It would appear that the question of whether additional factors (other than the prereceptoral ones) are involved in ageing could now be answered in a simple manner by examining relationships between the matching range and age. Ruddock tested over 400 subjects aged between 16 and 70 years at three wavelengths/

wavelengths 590 nm; 530 nm; and 490 nm. He found significant correlations between the discrimination step and age at 530 nm. and 490 nm. ($P < .01$) but no significance at 590 nm. Thus the results suggested that additional factors were involved, so that wavelength discrimination became poorer with increased age in the green and blue-green spectral regions. It is of great interest, therefore, that despite the significant correlations, this was not the conclusion reached in the study. The rejection of these significant figures rested on further observations of which two are of particular interest:- firstly that the relative discrimination (e.g. discrimination at 590 nm. as a ratio of that at 490 nm.) did not correlate significantly with age, and secondly, that in a follow-up study using only six subjects of different ages and a forced choice technique for data collection (See section II) the discrimination step did not increase with age. (In the major study RUDDOCK had used the method of limits to determine the matching range as did LAKOWSKI. As discussed earlier this is one of the classical methods in psychophysics which incorporates visual sensitivity and the response criterion in its measurement. On the other hand the response criterion cannot shift in the forced choice technique). Ruddock now considered the former significant correlations to be due to a shift in the response criterion and not due to a shift in visual/

visual sensitivity with age. Furthermore in addition to colour discrimination by the forced choice method, the other colourimetric functions measured by Ruddock did not indicate any age variation, while measurements of the photopic luminosity curve indicated age changes consistent with lens transmission data. Thus lens transmission was seen as the main factor responsible for age changes while the macular pigment was not a significant variable. The general conclusion, therefore, was that prereceptoral changes accounted for age changes in vision, and that age did not modify the receptoral colour response.

This is an excellent example of the influence of the psychophysical method on the inferential procedure. Although there was other evidence which certainly supported the general conclusion of the study, the initial significant correlations were now explained by postulating a response criterion change with age. The only evidence for this hypothesis was firstly, the observation that most of the young age group had had scientific training while the majority of the older group had not; and secondly, the lack of an age effect in a group of only six subjects using the forced choice technique. If this is correct, the response criterion shift must be responsible for the additional colour vision losses measured by Lakowski which could not be explained by prereceptoral absorption. (It has been

been assumed of course that the figures for prereceptoral absorption were not grossly underestimated).

If the inferences in vision research problems rest so heavily on the methodology of testing it would seem that a move towards the forced choice and signal detection procedures is essential for a study of this and other problems in which individual variability is of importance.

(iii) Effects on General Function

In addition to colour vision changes, the factors discussed on page118 result in several other measures of visual function changing with age. Visual acuity is likely to be modified by age changes in the lens and pupil diameter and, in fact, BANNISTER, HARTRIDGE and LYTHGOE (1946) have shown that visual acuity depends on retinal illumination. However once again methodological problems arise. For instance, Fig. 38 illustrates the relationship between visual resolving power and age. Apart from the decline in resolving power at the later ages the curve is noticeable for its growth at the early ages, where optimal performance is only reached after ten years. WEALE (1963) oxplained this growth on the basis of hypermetropia in juvenile eyes but also mentioned comprehension and intelligence as possible factors. However, it has been shown that if children are sufficiently motivated, visual acuity will reach the adult standards as early as three years of/

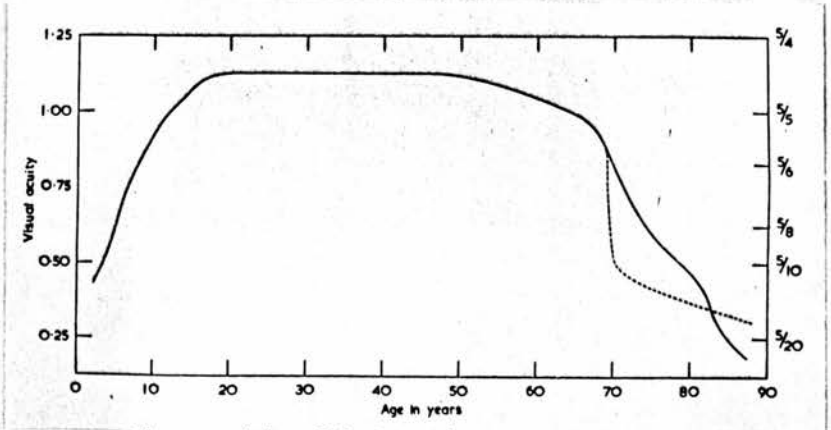


Figure 38

The age variation of visual resolving power. The dotted curve includes observers with incipient cataract (after Slataper, 1950)

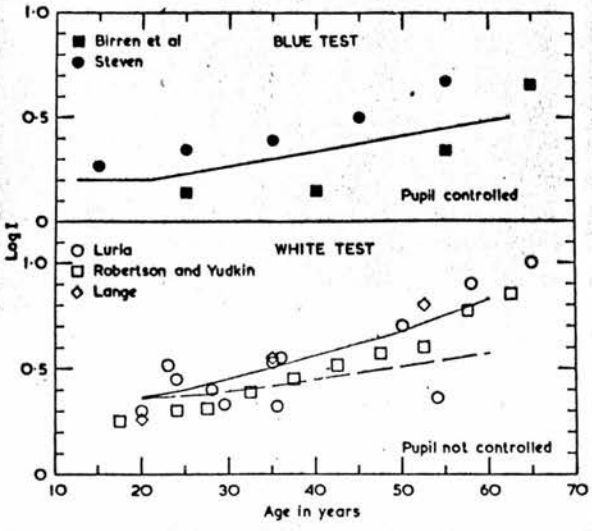


Figure 39

Top: when an artificial pupil is employed the absolute (rod) threshold, as measured with a blue test-field, increases with age. The full line indicates the extent of rise to be expected from the lens becoming yellower

Bottom: when a white test is used and the pupil area is not controlled the senile rise in threshold is more pronounced. The dashed line indicates the rise to be expected on the basis of senile miosis; the full line takes account of both senile miosis and lenticular yellowing (Weale, 1961*c*)

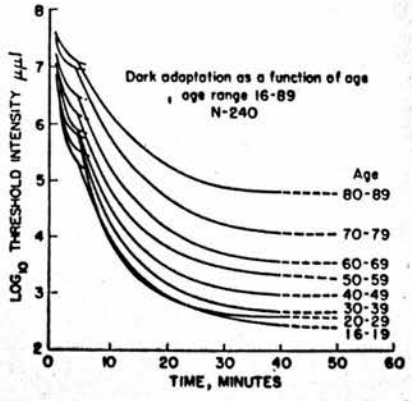


Figure 40

Dark-adaptation curves uncorrected for senile changes in the lens (McFarland *et al.*, 1960)

of age (McDERMOTT, 1969). It would appear, therefore, that Fig.38 does not represent resolving power as is claimed. The method of testing acuity has in it inherent psychological factors, which at least in the early ages, are far more important than the effects of hypermetropia.

In a similar way the critical fusion frequency (c.f.f.) changes with age so that there is a decline in the fusion frequency as age increases. In addition the c.f.f. decreases progressively as one moves from the centre to the periphery of the visual field (WOLF, 1962). However, once again there are correlations between intelligence and critical fusion frequency which are sometimes claimed to be more significant than those with age (COLGAN, 1954). WEALE comments "This sort of thing is typical of visual problems in general. In experiments involving objective measurements anyone can be wrong: in those essentially subjective in nature everyone can be right". Certainly there are instances of ambiguous evidence due to the methodology in testing visual function. However with the aid of methods outlined in Section II there is no longer cause for this type of pessimism. The validity of relationships in visual function can be re-examined by the newer methods and placed on a firmer experimental basis.

Other reported changes in visual function with age are as follows. The absolute threshold has already/

already been shown to be particularly sensitive to pupil size and so to change with age. Variations in the threshold appear to be explained on the basis of pupil diameter alone, as shown by Fig. 34 . However, further data on the absolute threshold by BIRREN, BICK and FOX (1948) using a controlled pupil indicated a general rise in threshold with increased age (Fig. 39) which was not to be expected on the basis of Fig. 34. Similar age changes in the absolute threshold were discovered by FANKHAUSER and SCHMIDT (1957), for both a visibility test and a test of visual acuity. Studies on the dark adaptation process illustrated significant changes in the recovery of sensitivity with age. An instance is shown in Fig. 40 in which the age changes are exaggerated by use of a violet test patch which is particularly sensitive to lens changes. (The age norms developed in the present study make use of test patches at longer wavelengths which reduce lens effects and consequently reduce the loss of sensitivity at older ages). The fact that the curves in Fig. 40 can be superimposed on each other by moving them parallel to the ordinate suggests that the rate of the dark adaptation process is unaffected by age changes.

Perimetry which forms another major part of the results' section is also subject to age changes. FEREE, RAND and MONROE (1929); GOLDMANN, (1945); MANN and SHARPLEY, (1947); JONKERS (1952); FANKHAUSER and/

and SCHMIDT, (1960); VERRIEST and ISRAEL (1964); ASPINALL (1967), have all shown a contraction in the field of vision with increased age. In addition, the technique of static perimetry has shown that with increasing age the gradient of the hill of vision becomes steeper so that for a given group of emmetropes the losses with age are greater in the periphery than in the fovea. The same problem arises as in the studies on colour vision. The decrease in absolute sensitivities has been accounted for by the decrease in retinal illumination due to a reduction of pupil area with increasing age, together with the increase in absorption of light by the lens. However, when the results of retinal sensitivity were corrected firstly, for pupil area, and secondly, for lens absorption, the values obtained for the older age group were still not as high as those for the young subjects. Furthermore, Verriest and Israel showed that by changing the spectral composition of the test target, there were differential losses in sensitivity to different coloured objects beyond those due to prereceptoral absorption. In kinetic perimetry variations in the area of the field of vision have been linearly related to variations in the logarithm of the pupil area (MAZZANTINI and WIRTH, 1962). This implied that the amount of light reaching the retina was the crucial factor in threshold sensitivity. By using a correction factor for pupil size, the values/

values for the size of the field were brought into line with values obtained with a pupil size of 4 mm. However, the discrepancy of 0.3 mm. between mean pupil diameter in the young group (20-40 years) and the old group (50-70 years) in MAZZANTINI's sample might underestimate the general relationship between age and pupil size (See Fig. 32). In a later paper (MAZZANTINI, 1963) the emphasis was placed on the lens as the important factor in age changes. The visual function changes with age occurred at a constant rate, and were thought to be due to the increase in absorption of the lens as this occurred at a constant rate with age.

In a statistical analysis carried out by ASPINALL (1967), there was only a small positive relationship between retinal sensitivity and pupil diameter. Within this relationship, pupil diameter had a greater effect on peripheral sensitivity than on foveal sensitivity. However, the age variable itself far outweighed the variables, pupil diameter and refraction, in accounting for the reduction in peripheral sensitivity in a normal retina. (Here the variable "age" includes lens changes, senescence of receptors, and any factors that might be subject to age changes). At the other end of the age continuum interesting changes were observed in the retinal threshold gradient of children. The younger the child, the lower the sensitivity at both the fovea and periphery compared with the optimum level of/

of performance of the 20 year old group. The peripheral changes were quite dramatic, and much larger than the foveal ones, suggesting a developmental increase in peripheral sensitivity between 6 and 11 years. There is no simple explanation of this growth. All parts of the visual system should be physiologically capable of receiving a light stimulus by six years. In fact the prereceptoral absorption of incident light is at a minimum in very young children (SAID and WEALE, 1959; WEALE, 1962) and dark adaptation studies of the final thresholds show them to be at their lowest in this age group. (DAVID, 1956; FANKHAUSER and SCHMIDT, 1957). It was surmised that in young children there is either a cortical suppression of peripheral information perhaps to allow perceptual development to take place in the foveal area, or that children have not learned how to deal with peripheral information. However, as classical methods were used in testing these children it was not possible to give any indication of likely causes.

A general picture of age changes has been given for both the colour changes taking place with age, and the general functional changes occurring with age. The reports have been deliberately general as it has been emphasised that the test which is used determines firstly, whether or not a loss will be detected, and secondly, the extent of the loss likely to be detected/

detected. Because of this, the age effect must be measured for each of the tests used in this study and defined specifically in terms of each test. This operational approach to visual function testing is stressed again in the following sections.

It has also been shown that many questions relating to age changes remain unanswered because the methodology of the test procedure prohibits a satisfactory solution to the questions which are asked of it. While this situation remains, evidence for or against a particular hypothesis will readily be available. This argument is particularly forceful if causal factors are sought as explanations of particular phenomena. It also applies when the aim of a study is to detect small colour vision changes where the extent of the change may well be of the same order as the error in the measurement. In this situation the use of techniques which give a measure of visual discrimination only is essential. On the other hand, in a comparison of a clinical population with a normal population, the variations in vision may well be sufficiently large to use alternative procedures. In such cases in which the age changes are simply tabulated to act as norms for clinical comparison, and where the weight of contributing factors to those age changes are not of importance, then classical methods are appropriate. (See Section II d.) for a further discussion of alternative methods).

V DEVELOPMENT AND ASSESSMENT OF TESTS

Introduction

In an assessment of visual function, it is recognised that no one test can cover the range and types of functional variations in vision. It is necessary, therefore, to have a battery of tests which supplement and complement each other. In this respect the test battery should:-

a.) be capable of detecting the range of acquired dyschromatopsias,

b.) meet practical requirements so that it varies in sophistication from routine screening tests to highly specialised research tests.

It is clear that condition a.) presupposes knowledge of the changes that are likely to take place. This situation is clarified by considering the nature of colour space and the CIE system (See Fig. 27). The CIE system assumes that colour anomalies, particularly those of the dichromats, are reduced forms of normal vision, and it is on this assumption that the confusion lines are developed from the spectral response curves. Although this assumption is questionable (See Section IV) the colour triangle still provides a useful model for explaining colour anomalies, and can be used to represent all visual anomalies from normal to complete achromatopsia. As the space is three dimensional it/

it is apparent that three vectors are sufficient to account for changes in this space. Consequently if colour changes alone are to be investigated, two vectors at right angles, representing two colourimetric equations, are sufficient. All other changes in the triangle can be resolved into the two perpendicular equations or axes. Similarly the brightness vector is at right angles to the plane of the triangle and accounts for luminosity differences. However, there are an infinite number of points in the triangle about which the colourimetric equations can be rotated; consequently there are an infinite number of colour vision tests. Most tests using surface colours, of necessity lie near the central regions of the triangle, while tests using lights can exist at all points out to the spectrum locus. Thus, the CIE system forms an essential basis for the analysis of the stimulus characteristics in a colour vision test and provides the best way of comparing the nature of different tests in a battery. The following description of tests is divided into those which are primarily tests of macular function, and those which fall under the heading of general function (including dark adaptation and perimetric studies).

a.) Macular Function

The first two tests to be described (Snellen Acuity and Ishihara pseudo-isochromatic plates)are probably/

probably the most popular ophthalmological tests of visual function. In this study no modifications to these tests have been made, but an assessment is included here because their widespread use required their inclusion in the test battery.

1. Visual Acuity Test (Snellen Letter Chart)

Visual acuity has been defined, PIRENNE (1962), as "the reciprocal of the angle in minutes subtended by the smallest detail which can be seen under given conditions". This is an operational definition and PIRENNE continues, "there are in fact as many different visual acuities as there are types of test object. A tendency to give visual acuity an ontological status has sometimes led to confusion". This point should be borne in mind when the Snellen acuity results are compared with the foveal differential threshold. This latter forms part of the retinal threshold gradient and represents the detection of a small spot of light (constant size, variable brightness) against a constant background luminance. In visual acuity testing, distinctions have been made between the minimum visible (or light sense), the minimum separable (or resolving power) and the minimum cognoscible (or higher order perceptual processes including interpretation and integration of the visual signal). It is the latter which is normally measured in the Snellen acuity test./

test.

Stimulus factors influencing visual acuity are listed by DUKE-ELDER (1968) as:-

(i) The region of the retina stimulated.

(ii) The intensity of illumination.

(iii) The distribution of illumination

(iv) The spectral nature of light.

(v) The time of exposure.

(vi) The effect of movement.

The regional variations (i) are to be expected, if only from the variations in receptoral distribution from the centre to periphery of the retina. At scotopic (low) illumination levels, which favour rod responses and not cone responses, the optimum acuity may be in a parafoveal region where rods predominate (MANDELBAUM and SLOAN, 1947). However, scotopic peripheral acuity does not follow the rod population frequency, nor the light sensitivity of the retina, which suggests that it is not the receptoral number which sets the limits to scotopic acuity but the assimilation and convergence of visual signals in the nerve fibres. Illumination changes affect acuity, so that acuity initially varies as a linear function of the logarithm of illumination and subsequently declines to reach a maximum at about 1,000 photopic trolands of retinal illumination (PIRENNE, 1948). Common acuity tests are generally black figures against a white background./

background. Contrast is an important determinant of the measurable acuity, and varies with the illumination level in the test situation. Black and white test charts obviate possible colour variations but acuity is generally poorest in short wavelength light (LURIA and SCHWARTZ, 1960). Exposure time is a further factor which is inversely related to luminance (Bunsen-Roscoe Law) up to flash durations of 0.1 sec. For durations of one or two seconds, luminance is the determining factor independent of duration. Peripheral retinal regions have a reverse effect (TROXLERS) where a continually exposed target disappears if fixation is good. Movement of the test object clearly influences acuity, and the dynamic visual acuity is generally less than the static and deteriorates as speed increases. LUDVIGH and MILLER (1958) considered the effect to be neuro-muscular rather than neuro-physiological.

According to SNELLEN (1864), a normal eye can separate two lines if their separation subtends 1' of arc. His letter sizes were based upon the results of his investigations on the resolving power of the average eye. A visual angle of 1' is accepted as a standard clinical level of normality, although the eye can resolve angular separation down to 30 or 40 seconds of arc (DUKE-ELDER, 1968, p. 610). It has been shown that the lower limit of visual resolution is imposed by optical effects such as diffraction resulting from the nature/

nature of light, and is not due to the fineness of the retinal mosaic (GRAHAM, 1966, p. 327). The value of 30 seconds of arc is close to the limit expected on optical grounds.

Nevertheless, it is implicit in Snellen's thinking that the perception of letters is effected by means of a visual separation of parts in spite of their total configuration. However, later research with test types has shown wide differences in legibility among letters despite their having an overall subtense of 5' of arc and component limbs of 1' of arc, (BENNETT, 1965; RABIDEAU, 1955; SLOAN, 1951). Consequently, a rigid interpretation of the optometric principle has taken no regard of the informational content in the stimulus, which varies from one letter to another. Perceptual processes do not appear to be determined by the simple optometric principle, and the recognition of a letter need not depend on the visual separation of parts. Separation, while playing a part in letter discrimination is certainly not the sole factor in operation. It would appear that the legibility of any letter is a function of the "Gestalt" of which it is a part, and will vary with the total number and varieties of letters which can be selected in making a response (RABIDEAU, 1955) More recently GARNER (1966) has shown that perception depends not on the stimulus object alone but upon the properties of the set of which the stimulus is a member./

member.

It is sufficient to state that notions of perception which assume the whole to be determined by the sum of the parts are no longer tenable. The above problems, inherent in the use of letters as stimulus objects, become of greater importance in testing the visual acuity of children (McDERMOTT, 1969). This suggests that intelligence may be correlated with visual acuity tests and be particularly relevant in testing the broad spectrum of individuals making up a clinical population. If this is the case, cognoscible tests should be avoided, as they are particularly susceptible to non-visual factors.

General conclusions are:-

Visual acuity is defined operationally so that there are as many acuities as test objects. Because of this the results from the Snellen acuity test are not transferable to other acuity tests using a different stimulus object.

While the Snellen acuity test is useful as a gross measure of visual function, perception is governed by complex factors which go beyond the optical components in the test. As a result the letters making up the Snellen test differ in legibility in spite of the optometric principle. This makes the test of little value as an accurate assessment of visual function particularly in a research context./

context.

2. Pseudo-isochromatic Plates (PIC tests)

These tests involve either the reading of numbers, (Ishihara) or the recognition of symbols (American Optical, Hardy-Rand-Rittler, AOHRR). They include, therefore, the drawbacks mentioned in connection with letter recognition in the Snellen Test, in that they are cognoscible tests and are consequently subject to non-visual factors. The most extensive work on PIC tests has been carried out by LAKOWSKI. All the evidence mentioned in this section stems from his work, These tests are important because they are designed to be screening tests administered in a short space of time, and they represent the most widely used form of colour vision test.

The tests are called pseudo-isochromatic because while normal observers can distinguish their colour and identify numbers in them, they are isochromatic to defective vision. From the perceptual point of view, plates using symbols (e.g. triangles, circles) are easier to recognise than those using numbers. Numbers introduce ambiguity in recognition, if a few of the colours in the plate are confused, (LAKOWSKI, 1965b.). This emphasises Garner's point (page 143) that properties of the set influence recognition. In the AOHRR plates only three symbols are used; circle, cross and triangle./

PHOTOMETRIC CURVES IN P.I.C. TESTS

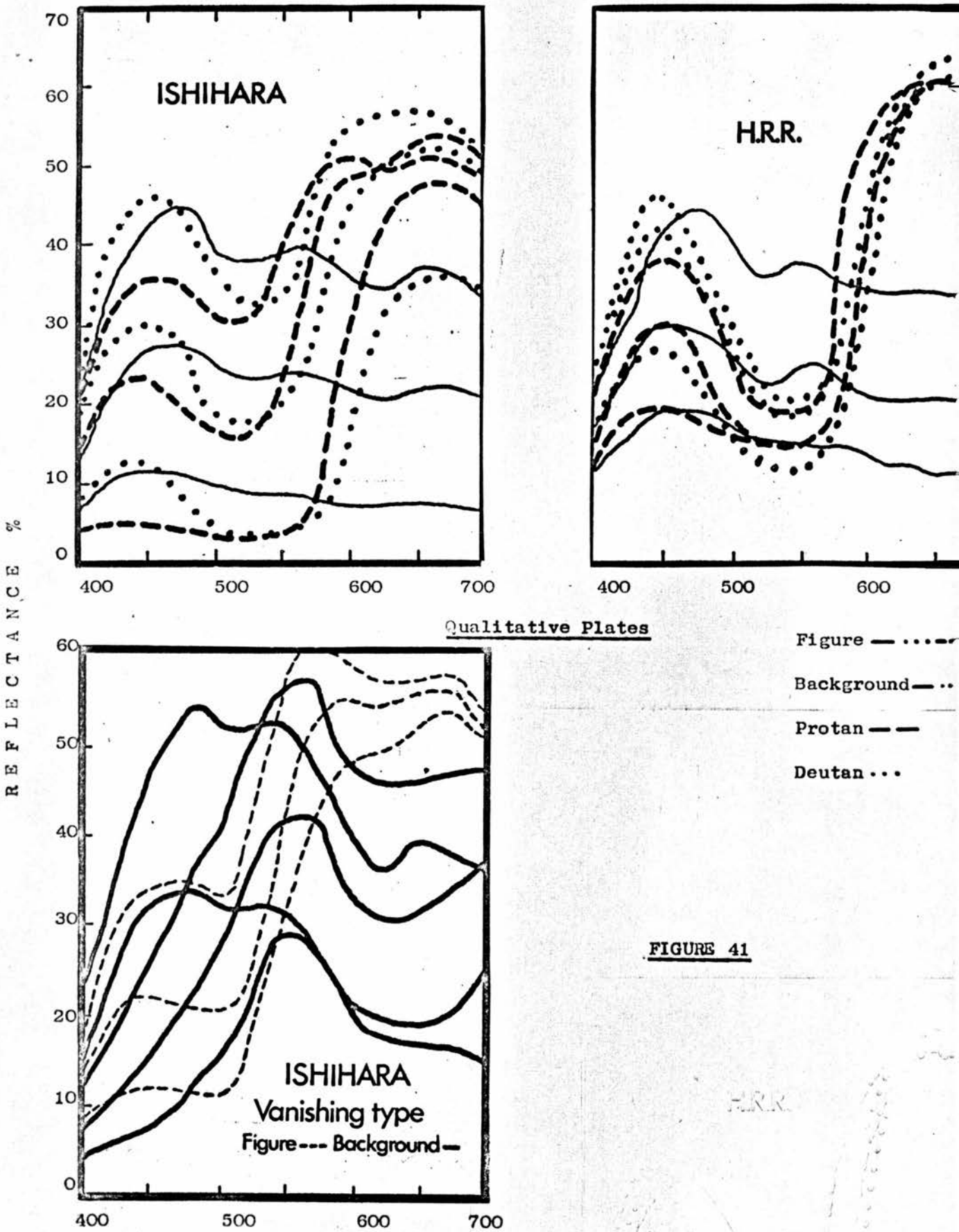


FIGURE 41

triangle. However, in the Ishihara the "set" is considerably larger as all single or all two digit numbers are possible. Recognition in the first instance is much simpler than in the second.

(i) Stimulus Characteristics

Prior to Lakowski's work, test assessment depended upon diagnostic criteria; that is a test was a good one if the majority of defectives failed it. However, by use of spectrophotometry and colour measurement, Lakowski was able to give a new appraisal of colour vision tests. Spectrophotometry is the measurement of reflectance curves. In the case of surface colours, it provides information on the pigments used to make up the test. It is the basis for all subsequent colourimetric calculations and so is dealt with first.

Reference to surface colours as broad band stimuli has already been made (page 74). Because monochromatic stimuli are not possible with surface colour, tests using pigments always include more than the hue variable, and any particular colour may have subsidiary peaks in its reflectance curve. Fig.41 illustrates the complex nature of relfectance curves in the Ishihara and AOHRR tests. As Lakowski points out, in this situation the colour response evoked in a normal observer may be quite different from that in the acquired or congenital defective and quite different from that intended in the test construction. The intended stimulus characteristics/

characteristics are therefore, changed in accordance with the nature of the colour deficiency. In addition the more metameric the nature of the stimulus, the more it is affected by changes in the illuminant. (Illuminants C or D are recommended for this test.) It is not sufficient to point to the colours seen by the normal observer as distinct, and infer that they are the only colours in the test. If the stimuli are metameric, slight anomalies in vision may yield "apparent colours" based upon changes in the visual input. It appears, therefore, that paradoxically the simple screening test turns out to be complex from both the perceptual and the stimulus viewpoints.

The construction of PIC tests falls into four general categories. These are, the vanishing type plate; the qualitatively diagnostic plate; the transformation plate; and the hidden digit plate. The first two types are used to illustrated the photometric analysis. The vanishing type plate in Fig.41 is the most frequently used in PIC tests, as it is read by normals and not read by defectives. The qualitative diagnostic plate on the other hand is composed of two separate figures enabling one to be read in one particular defect, and the other read by individuals with a different defect. In the Ishihara, this plate is used to distinguish between Protanopes and Deuteranopes. In the Ishihara and the AOHRR the qualitative plates have/

LOCATION OF P.I.C. TESTS IN THE C.I.E. DIAGRAM

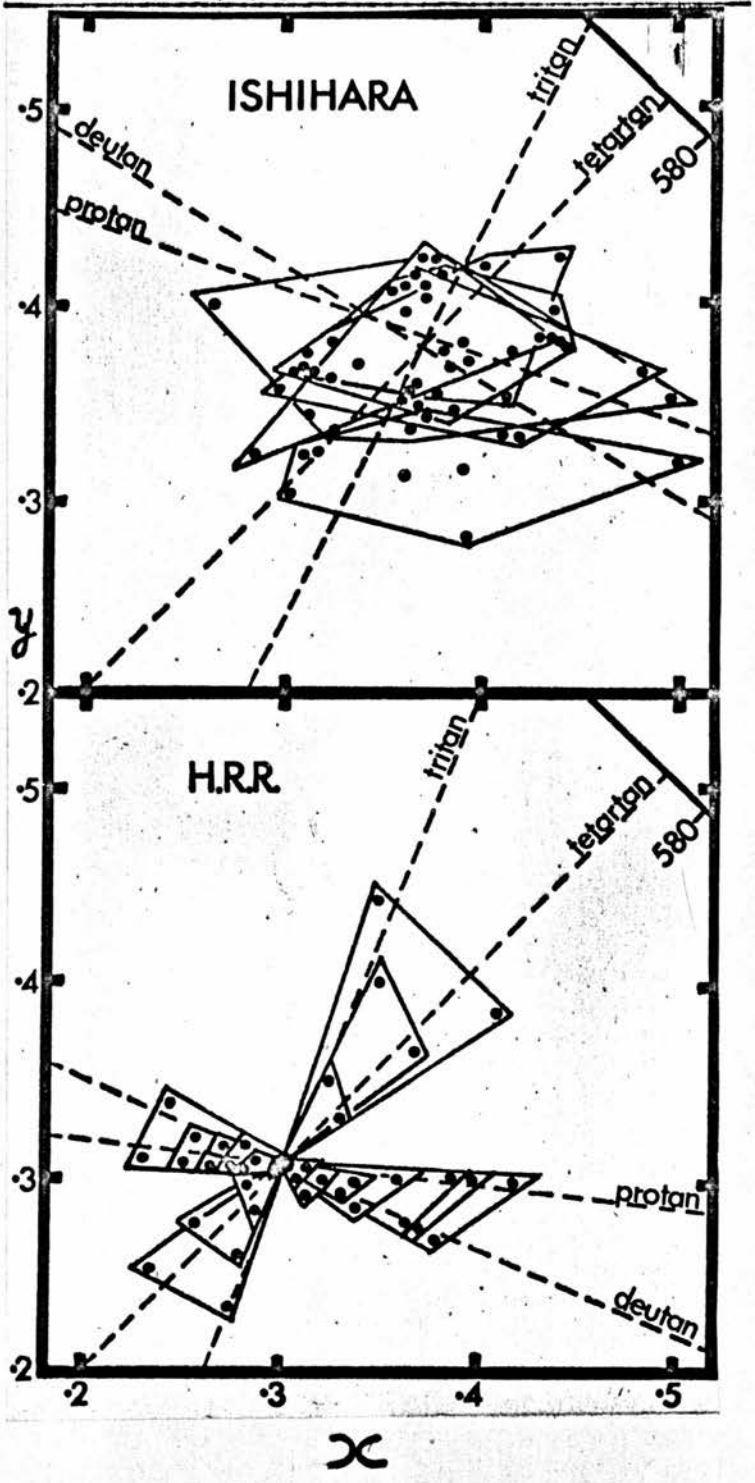


Figure 42

have neutral greys as background. Three colours are used for the deutan figure and three for the protan. In either case these tend to be of the minus green type with two clearly marked reflectance peaks (Fig. 41). The differences in reflectance curves between colours used for the figures and colours used for the background may be large enough to make us cautious in expecting all but outright dichromats to respond in an identical manner to these various plates (LAKOWSKI, 1965). Consequently other visual anomalies may produce different readings among the different plates.

In the photometric analysis it is assumed that similar reflectance curves result in the same sensation. Conversely, the reading or non-reading of a plate depends on the difference in the reflectance curves between figure and background. Colourimetric analysis extends this relationship between stimulus and sensation and is more closely related to psychophysics. In colourimetry quantitative predictions can be made concerning the difficulty of reading a particular plate based on the calculation of colour differences between the figure and background. Furthermore in tests designed to detect and diagnose dichromats, an immediate check can be made upon whether the colours of the figure and background fall upon the dichromatic confusion lines. These are the two principal factors tested by PIC tests.

Fig. 42 illustrates the general positions of the Ishihara and AOHRR tests in the CIE triangle. The/

The relatively random scatter of the Ishihara test illustrates the trial and error nature of its construction. (It is the earlier of the two tests and was developed before the existence of colour confusion theory). On the other hand the AOHRR test is constructed to comply with requirements of colour confusion theory. Here the central grey is common to all plates and acts as a background. Each plate is designed to form a triangle with the apex at the position of grey. The colours in this test are arranged upon two principal axes of red-green and yellow-blue confusion lines. It is generally true that the greater the distance from the apex of the triangle to the colour forming the figure, the greater the loss in colour vision necessary before the plate is confused.

Two of the four types of PIC plate, vanishing type plates and qualitatively diagnostic plates, have alreaay been mentioned. Two further types are transformation plates, in which both normal and defective observers can see figures but each identifies different ones; and hidden digit plates which are based on the converse principle of being read by defectives and not read by normals. (Four plates of the Ishihara are designed on this principle. However, the hidden digit plates were not scored in this study but were used only to reassure dichromats of the presence of numbers./

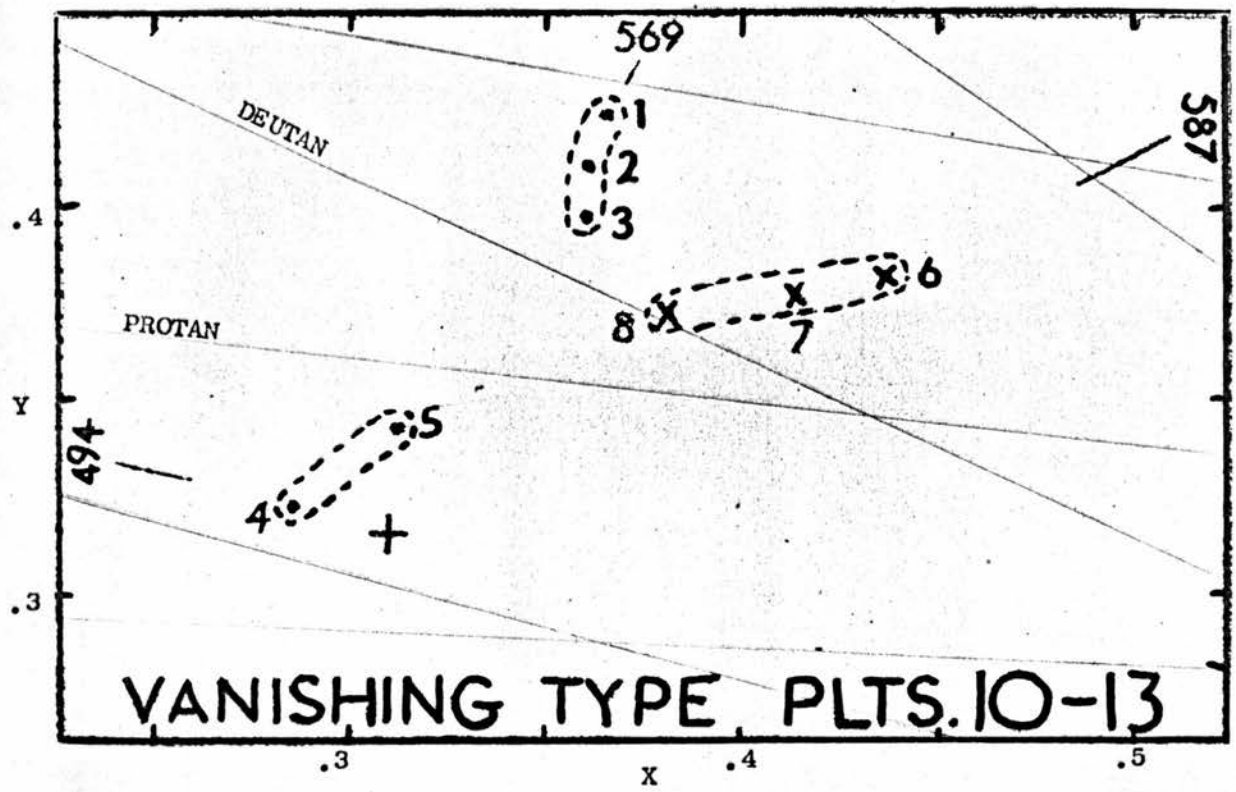


Figure 43 COLOURIMETRIC DATA

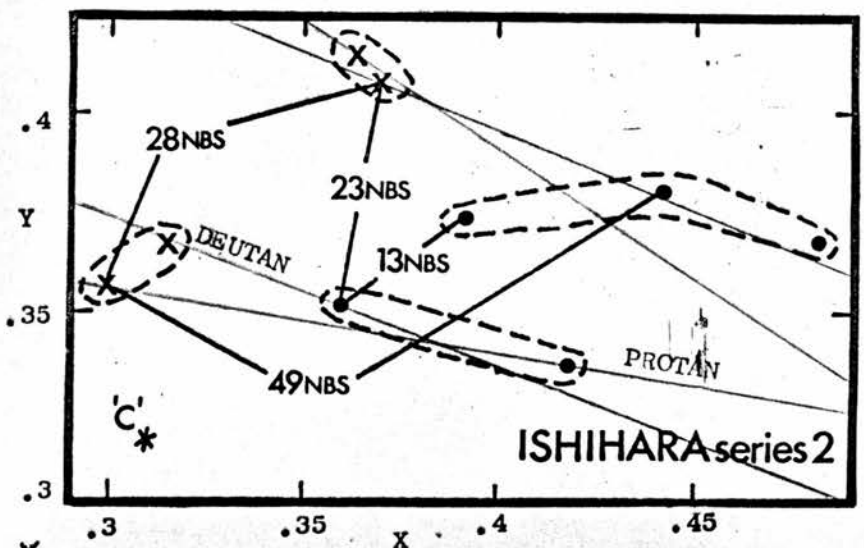


Figure 44 FIGURE X

BACKGROUND •

numbers. Although designed on the reverse principle Lakowski found that 40% of subjects in the 20-30 year age group can read these plates.) The vanishing, transformation and qualitatively diagnostic plates are used to illustrate the value of colourimetric analysis.

Colourimetric data for the vanishing type plate is given in Fig. 43. Eight of the Ishihara plates are based on this principle (Plates 10-13 and 14-17). In the second group of four, a yellow is added to the background which is close to the colour of the figure. The number of misreadings in this second group fits the expected increase in difficulty of these plates. Error values are 12% for the first four, and 22% for the second four. The plates, therefore, differ in difficulty depending on the distance between the figure and background. Methods of calculating this difference, in colour difference units, have been devised. The one used here is the Nickerson-Stultz formula (See JUDD, 1959), which gives the difference between two colours (Δ c) in NBS units (National Bureau of Standards). One NBS unit is equivalent to approximately 5 j.n.d.'s (just noticeable differences), for a normal observer. In the calculation of Δ c the non uniformity of the CIE chromaticity space (as shown by the variation in MacAdam ellipses, Fig. 27), cannot be used, and the system must be transformed so that equal physical distances in the triangle represent equal/

COLOURIMETRIC DATA FOR THE QUALITATIVELY DIAGNOSTIC PLATES

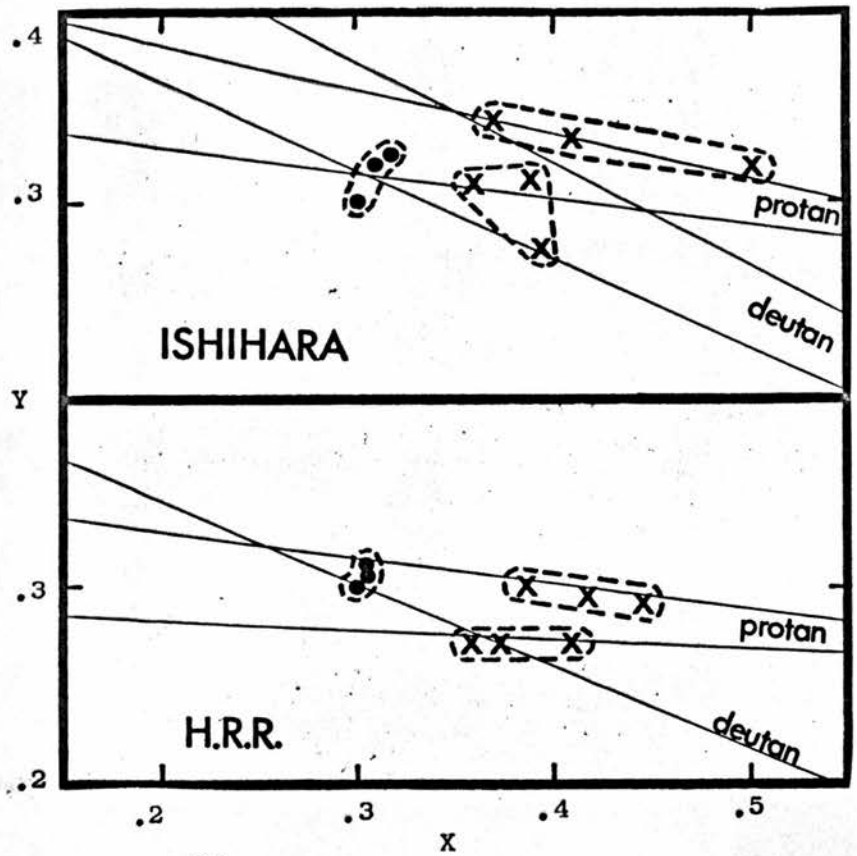
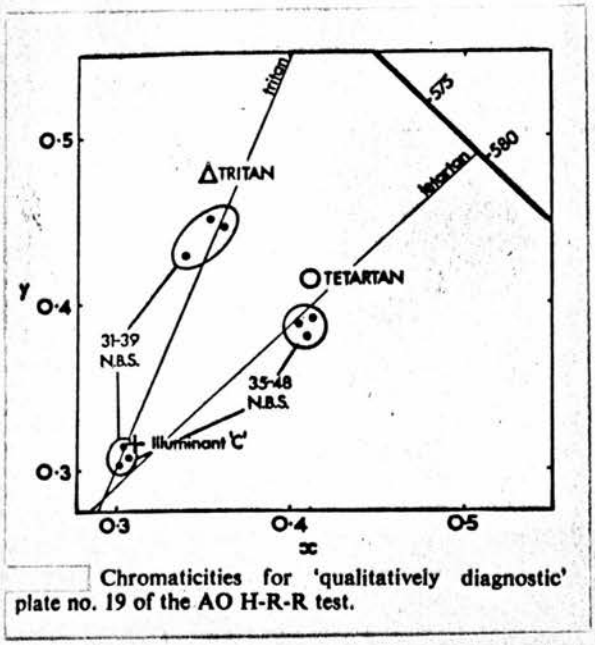


Figure 45

Figure ✕

Background •



Chromaticities for 'qualitatively diagnostic' plate no. 19 of the AO H-R-R test.

equal visual steps. (This is discussed in greater detail for the Pickford Nicholson Anomaloscope.) However note that Δ c is calculated from brightness as well as colour differences.

This information is illustrated in Fig. 44 for a transformation type plate (No. 9) of the Ishihara (reading 74 to the normal observer). The figure is green against a reddish background with a hue difference of 15 nm. in dominant wavelength between them. Nine colours are used, which are arranged in four groups, two for the figure and two for the background. However the dichromatic confusion lines of the protanope and the deuteranope illustrate that half the colours of the normal background and half the colours of the normal figure are reversed, so that the new figure is composed of half the normal background and half the normal figure. Consequently, in plate No. 9, reading 74 to the normal observer, the deuteranope and protanope reads 21. In individuals with visual defects falling between those of the normal and the dichromat, and in children and old people, a mixed response occurs. In this latter category roughly 50% of subjects read the plate as 71.

The qualitatively diagnostic plates are illustrated in Fig. 45 . These are simply two vanishing type plates incorporated into one by the use of two differently coloured figures and one common background. How successfully/

successfully the plates have been constructed can be seen from Fig. 45, which illustrates the principle for both red-green and yellow-blue defects. Consideration of the protanope and deuteranope confusion lines shows that they show the greatest difference in slope away from the red-green spectrum locus. Tests to differentiate protanopes from deuteranopes should make use of this fact, although it is seldom followed in test construction. Both the Ishihara and AOHRR tests use some colours in the "deuteranope" figure which lie along the "protanope" confusion lines. This implies that the protanopes should have difficulty in reading this figure. Lakowski found this to be the case. In terms of correct reading according to the test design, only 22% of protanopes read correctly while 88% of deuteranopes gave correct responses.

The Ishihara is principally a red-green test and no plates exist in it for detecting yellow-blue defects. The more recently devised AOHRR, however, does include plates specifically for both tritanopic and tetartanopic defects (See Fig. 45). In general the qualitative diagnostic plates contain large differences between figure and background (approx. 40 NBS units). This means that they are only likely to be misread by dichromats or monochromats.

The usefulness of colourimetric analysis should now be apparent. The stimulus characteristics can be/

be analysed from a general level of discrimination and test difficulty (Δ c measurements) and also from a colour confusion viewpoint. LAKOWSKI (1965) found that the qualitatively diagnostic plates always had the largest Δ c between figure and background while the quantitative and screening plates had smaller values of Δc. For the AOHRR screening plates Δ c was 20 NBS units, for the medium red-green defect $\Delta c \geqslant 36$ NBS units and for extreme red-green defect $\Delta c \geqslant 42$ NBS units. This illustrates an attempt to measure the degrees of defect in a test, in which the test order of presentation is important. In the Ishihara test, designed as a dichotomous test, all plates should be equally difficult and therefore the order of presentation unimportant. However, it has already been shown that this is not so, and Δ c calculations vary from 45 NBS units to 10 NBS units.

(ii) Test Criteria

Studies of colour vision using the Ishihara test have tended to show a lack of continuity between normal and abnormal vision. (PICKFORD, 1950; BELCHER, GREENSHIELDS and WRIGHT, 1958). However, LAKOWSKI (1966) pointed out that these studies were carried out on students, and were not representative of a random sample. Consequently ageing effects, minor pathologies and the scoring method blur these distinctions. The mean number of misreadings for the Ishihara varies with age/

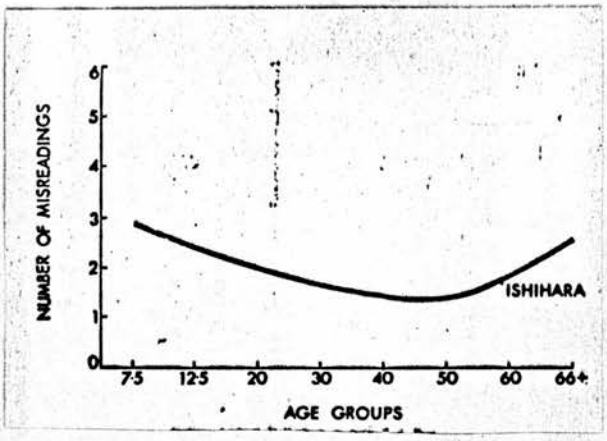
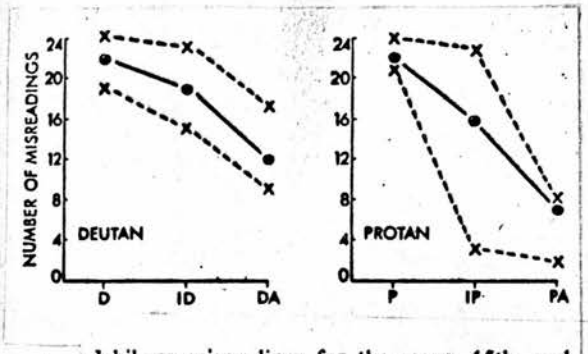


Figure 46

Mean number of misreading for an age population on Ishihara test.



Ishihara misreadings for the mean, 15th, and 85th percentiles for deutan and protan types of defects; dichromats (P, D), incomplete (IP, ID), anomalous (PA, DA).

Figure 47

age as in Fig. 46, showing the smallest number of misreadings at 40-50 years. The normal criterion for normal observers is not more than three mistakes on the Ishihara at first presentation (BELCHER et al, 1958). Such a criterion is seen to be misleading because at the young and old ages, the mean score of the normal population has risen to three errors. Half the normal group at these ages would require retesting if the criteria was applied. However, if the criteria is moved to a higher number of misreadings, some red-green defects will be included in the normal group. The solution is to regard the test as an indication of the probabilities of individuals belonging to particular categories; so that for instance, if an individual makes seven mistakes on the Ishihara test, the probability of him being an anomalous trichromat (PA or DA) is 0.7, if he is between 20 and 30 years of age. It is clear, therefore, that it is not possible to indicate the degree of a defect with any certainty. A consideration of Fig.47 will clarify this. Subjects who fell into either the dichromat or anomalous trichromat group, as determined by an anomaloscope, were examined for misreadings on the Ishihara. The mean and two other percentile points are given to indicate variations within each group. This data is summarised in Table I. The overlap between the performance of normals and red-green defectives is particularly evident for the/

the anomalous trichromats. In the case of a subject misreading 24 plates (including the hidden digit plates) the probability that he is red/green defective is 0.9. (Acquired anomalies due to disease processes make up the remaining 0.1 in a normal population). The probability of the subject being an outright dichromat is 0.80 indicating that there are a certain number of anomalous trichromats who can make this number of errors as shown in Table I.

General conclusions on the pseudo-isochromatic plates are:-

1. The Ishihara test is designed to detect red/green defects while the AOHRR test has plates for both red/green and yellow/blue deficiency.
2. The AOHRR plates test degrees of severity of colour defects so that presentation order is important. The Ishihara plates do differ in difficulty, as indicated by Δ c calculations, but the test is principally a dichotomous one between normal and abnormal vision.
3. Although these tests are regarded as simple screening tests, they are extremely complex from both the perceptual and the stimulus points of view.
4. A normal criterion score of 3 errors is misleading. It is most meaningful to regard error scores as an indication of the probability of an individual belonging to different categories./

TABLE 1

PIC test	*Outright dichromats*		*Incomplete*		*Simple anomalous trichromats*	
	Protan	*Deutan*	*Protan*	*Deutan*	*PA*	*DA*
Ishihara misreadings	*N = 21*	*N = 23*	*N = 13*	*N = 46*	*N = 6*	*N = 19*
Highest	24	24	24	24	22	22
Mean..	22	22	16	19	7	12
Lowest	20	18	2	6	1	1

Distribution of Incorrect Reading of Red-Green Defectives

for Ishihara

TABLE II

VERRIEST'S AGE POPULATION IN DECADES
(AFTER KINNEAR, 1965)

Mean age	*N*	*Mean score*	*σ*	*Scores*		*95th Percentile*
				Lowest	*Highest*	
10s	56	51·5	28	8	124	100
20s	145	40	31	4	162	92
30s	70	56	34	8	176	120
40s	62	76	37	16	184	144
50s	69	83	38	12	176	164
60s	29	88	35	28	174	152

categories./

5. Although the Ishihara is a red/green test it will detect subjects with serious losses in colour discrimination whether in the red/green or yellow/blue regions. Many clinical patients "fail" the test due to a general deterioration in vision.
6. The age of the subject has a bearing on the likely number of errors to be made in the test.
7. The tests are best used as part of a battery of tests rather than as a single indication of colour vision defects.
8. As 40% of young subjects can read the Ishihara hidden digit plates, they were not included in the scoring system of this study. Total error scores are, therefore, out of 20.

3. The Farnsworth Munsell 100 Hue Test

This test, devised by FARNSWORTH (1943), consists of eighty-five Munsell colours, each 1.2 cm. in diameter. The test is divided into four boxes each containing twenty-one caps. The four boxes vary in colour from pink to yellow; yellow to green; green to blue; blue to pink. The colours were chosen by Farnsworth so that young subjects with normal vision could just discriminate the difference between adjacent caps. The colour change within each box is a gradual/

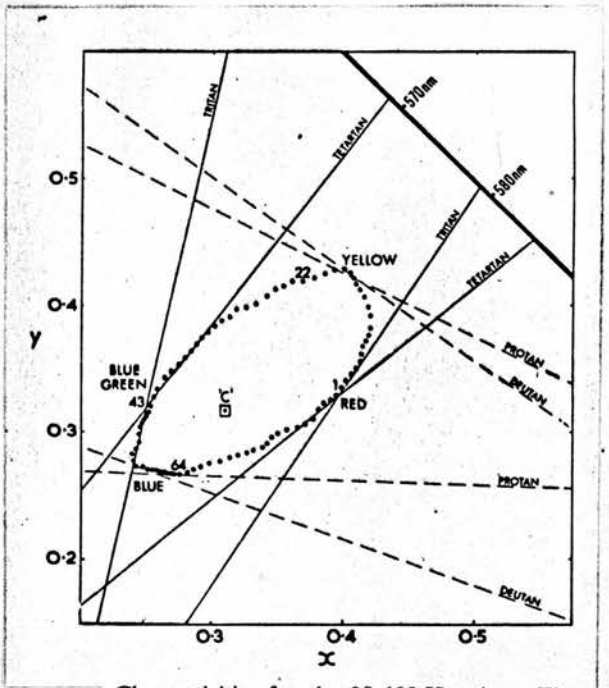


Figure 48

Chromaticities for the 85 100-Hue caps. The tangential isochromatic lines show areas where dichromats have poor discrimination.

gradual one, and the task of the subject is to arrange the caps to form a gradual colour series between the two end caps. There is a correct position for each cap in the series, and the caps are numbered for scoring purposes. In a correct arrangement the numbers run consecutively. In a misarrangement of caps, the errors are calculated for each cap by adding together the difference between the number of a cap and the number of caps on either side of it. In this scoring system, a perfect arrangement results in an "error" score of two per cap. Consequently the final score is obtained by subtracting two from the error score for each cap thus giving a baseline of zero in a correct arrangement.

The location of caps in the CIE space is shown in Fig. 48 . The caps were selected to differ in hue(or dominant wavelength) but to have the same lightness and saturation. Colour discrimination in the test must be by hue alone, and the colour defective cannot use other cues to detect differences between the caps. The test is administered under illuminant C or D at 30 lumens/ft.^{2} (or 300 lux), and a time of two minutes is recommended for each box. In the modified test procedure this was not adhered to, and subjects were allowed to continue beyond this time providing constructive moves were being made.

Colourimetric analysis by LAKOWSKI (1966), showed/

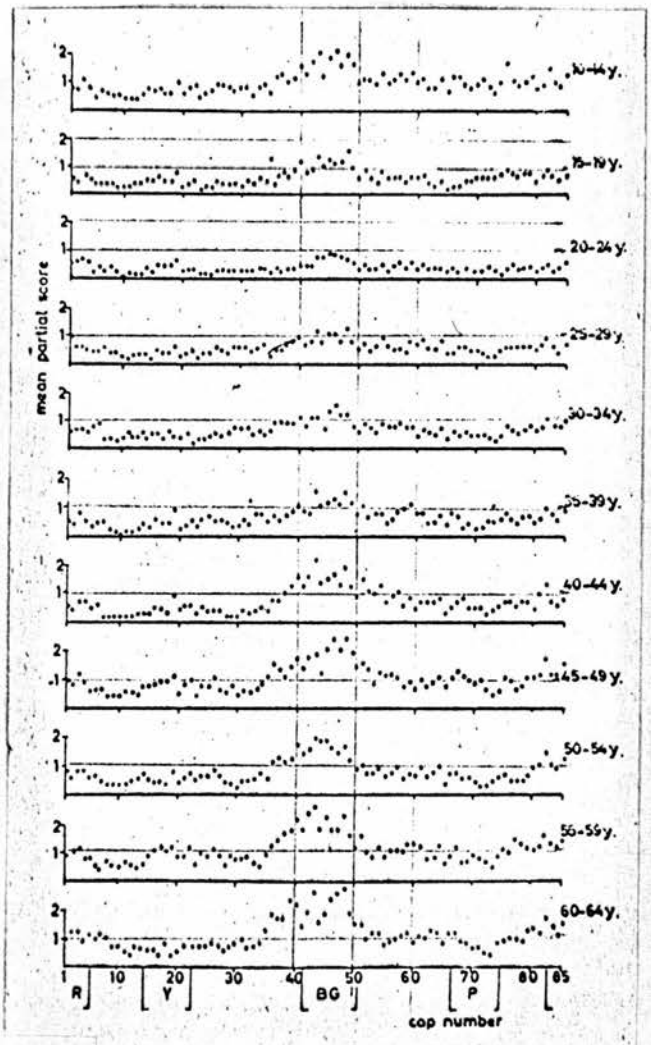
showed that the colour difference between consecutive caps was small and varied from 0.6 to 5.7 NBS units. The average colour difference between adjacent caps was 2.5 NBS units. Summing the colour differences over a box showed that the least sum was in the box containing caps 43-63 (consequently, this is the most difficult box); and the maximum sum was in the box containing caps 85-21 (the easiest box). Thus Farnsworth's attempt to obtain equal visual steps between adjacent colours did not succeed. This is given support from test scores in different age groups (See page 159). There are two properties of the test to consider. Firstly, a total error score which gives the sum total of errors throughout the spectrum, and secondly, a partial error score which shows in what region of the spectrum errors have occurred.

(i) Norms

According to the test manual, the following three categories may be used to assess test performance of the total error score:-

1. Superior discrimination: 16% of population (excluding defectives) score between 0 and 16 on the first test.
2. Average discrimination: 68% score between 20 and 100 on the first test.
3. Low discrimination: 16% score more than/

* Note: See page 173 for the upper limit of visual performance.



Color discrimination and age. Mean partial scores for each cap of the 100-Hue Test.

Figure 49

than 100 on the first test.

These criteria, however, broke down when the test was used on age studies. The most comprehensive of these was carried out by VERRIEST, (1963) based on over 400 subjects. The mean, standard deviation, and 95th percentile cut off point in different age groups is shown in Table II. (The standard deviation is not strictly appropriate here as the distribution is positively skewed. KINNEAR (1970) has shown that a square root transformation is most effective in normalising the distribution of scores in a normal population). The Table indicates that the limits of normality range from a score of 92 in the 20 year old group, to 174 in the 60 year old age group. These differences are statistically significant. Kinnear has shown the same sort of relationship in a smaller Scottish sample. In addition the increase of errors with increased age was not evenly distributed over the whole test. There was a disproportionately larger increase in the blue/green and red areas of the test, than in the yellow and purple regions (Fig. 49). An analysis of covariance showed this increase to be significant in the youngest and oldest age groups compared with the 20-30 year olds. It appeared, therefore, that:-

1. Age affected total test scores and necessitated norms for each age group./

group.

2. Age effects were particularly apparent in the blue/green and red regions of the test.
3. Within any age group the largest component of the error score occurred in the blue/green and red test regions. This confirmed the colourimetric findings that the visual steps were not equal between adjacent caps. They tended to be too small in the blue/green and red regions even for subjects with best discrimination.

The performance of colour defectives on the test is illustrated in Fig. 50. Dichromats are readily discernable because they make large errors in specific regions of the test, producing a bipolar bulge in the 100 hue profile. This is in keeping with colourimetric analysis which shows the dichromatic confusion lines to be tangential to the test in just those areas where maximum errors are made. The test was not designed to detect anomalous trichromats and does not do so. However, the extreme anomalous trichromats and incomplete dichromats sometimes make a monopolar bulge in the 100 hue profile in the test region where their dichromatic form makes errors. Two further profiles of interest are the anarchic and the scotopic. The first simply indicates an overall loss in colour discrimination throughout the spectrum. The second/

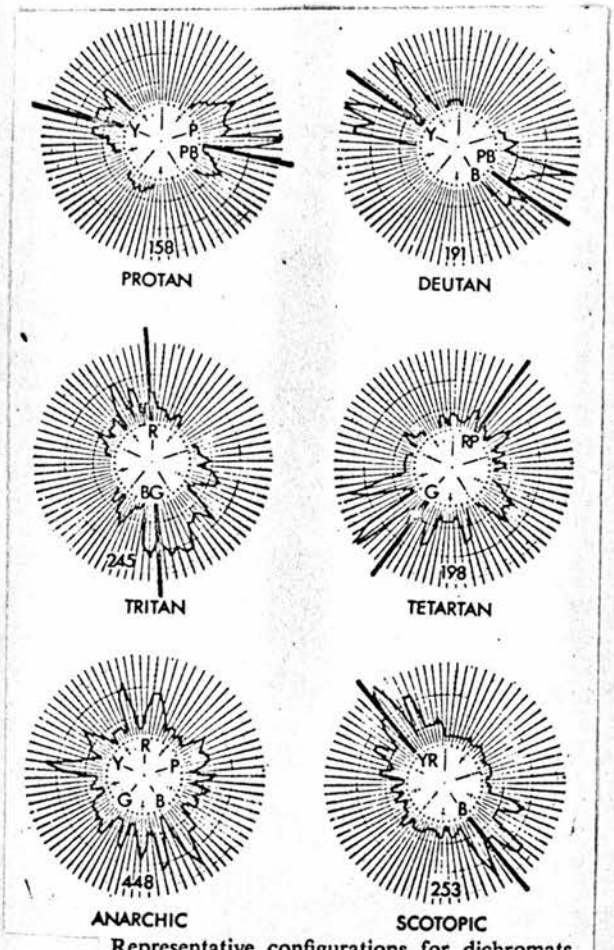


Figure 50

Representative configurations for dichromats and the anarchic and scotopic patterns, showing characteristic axes, profiles, and total error scores for each type of defect.

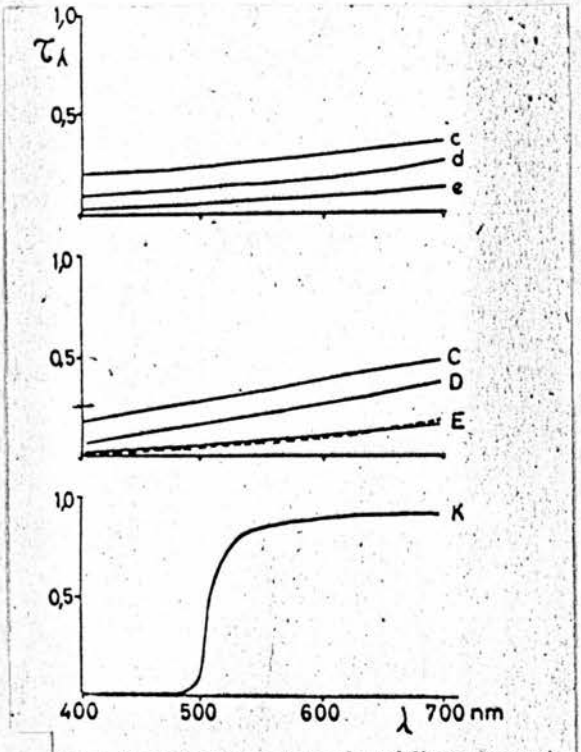


Figure 51

Color discrimination and wearing of filters. Spectral transmittance curves of the used filters.

second results from an alteration in the luminosity function from photopic to scotopic. The 100 hue caps were chosen so that the photopic luminosity of all caps was approximately equal. However, if the observer's vision has deteriorated until it is close to the scotopic luminosity curve, then there is a change in apparent brightness between those caps in box two, and those in box four. Boxes two and four can then be correctly ordered by a brightness difference. Boxes one and three also now appear different in brightness but because this difference is not systematic, the boxes cannot be correctly ordered by brightness alone. The result is the scotopic axis as shown in Fig. 50.

It is evident that the shape of the profile forms an important diagnostic index of the type of vision in addition to the total error score. Fig.50 indicates that the test region confused by tritanopes is precisely the same region which suffers the disproportionate losses due to ageing. It is apparent, therefore, that a pseudo-tritan axis can result due to ageing, resulting in a false diagnosis if age norms are not taken into account.

The test manual recommends two test sessions, the second of which is scored. However, VANDEVYVERE and VERRIEST (1963) found a high correlation (Spearman's $\rho = 0.93$) between a first test score and a second test score after an interval of two months. This/

This is important in a clinical context as considerable time is saved by only giving the test once, and the correlation indicates that this is a valid procedure.

The understanding of the concept "series", is necessary before subjects can be tested. The test may, therefore, be limited when applied to either individuals of very low intelligence or to children. There is evidence to suggest that children do not attain the full concept of seriation until at least seven years (PIAGET, 1928). There may be alternative methods of presentation which circumvent this problem (Lakowski, personal communication), but seven years would seem to be the very lowest age at which the test can be administered using standard instructions. However, the age changes illustrated in Fig.49 also show that the performance of teenagers is worse than that of young adults. It is not clear why this should be so. The reason may be physiological, as shown by the shift in mid matching point on the red/green equation in this age group (LAKOWSKI, 1964), or it may be psychological and related to motivation and the response criterion. VERRIEST (1963) found no correlation between the test and an attention factor among students. There was also no significant difference between the scores of a random sample and of professional colour workers.

(ii) Experimentally produced variations in Test Score

Two of the most important contributions to/

to ageing are certainly the lens changes and the retinal illumination change (See page 118). VERRIEST, BUYSSENS and VANDERDONCK (1963) studied illumination changes on the 100 hue test with 25 students. The authors found that the results could be considered normal down to 15 cd/m^2. However, below this, errors increased until tritan type defects began to appear, and finally at low illumination levels the scotopic type of defect appeared. The error zones were centred on caps 3 and 45 at an illumination of 4 cd/m^2 (tritan axis), whilst at 0.05 cd/m^2 there was a rotation of the axis so that maximum errors appeared at caps 12 and 54 (scotopic axis). Limits to the photopic level are 100 trolands (10 cd/m^2) according to LE GRAND (1948). Correlations showed that the subjects performing best at normal luminance levels tended to perform best at low illumination levels; and similarly those performing worst at normal illumination levels remained worst at all lower illumination levels. The score of subjects with acquired dyschromatopsias was found to deteriorate at moderate illumination levels at which the normal was unaffected. The authors suggest that the acquired yellow/blue defect is a mesopisation of normal photopic vision.

As an extension of this experiment, VERRIEST (1963) carried out further studies with young subjects who performed the test through coloured filters. Some of/

of the filters were almost non-selective regarding wavelength, with only a slightly lower transmission at 400 nm. than at 700 nm. A second group of filters (Fig.51) were more selective in transmission with optical density 2.5 times greater at 400 nm. than at 700 nm. Finally, a filter was used which absorbed all wavelengths less than 500 nm., but transmitted all other wavelengths. Transmission factors were calculated for each filter. Mean error scores for a group of 43 subjects aged 20-25 years increased under all the filters. The standard deviation of the group results under any filter, was also greater than under normal viewing conditions. Furthermore for equivalent filter transmission, there was a greater breakdown in vision under the selective filters than under the non-selective filters. Consequently when the shorter wavelengths were more selectively absorbed, error scores on the test increased. It will be recalled that experiments in which the illumination level was reduced showed that vision was normal down to an illumination level of 15 cd/m^2. As the luminances under the filters were considerably brighter than 15 cd/m^2 the results supported the hypothesis that selective absorption is more detrimental to visual performance of the test than a reduction in illumination. Those individuals with highest errors without filters again had the highest error scores when wearing the filters. As in the previous study the errors were/

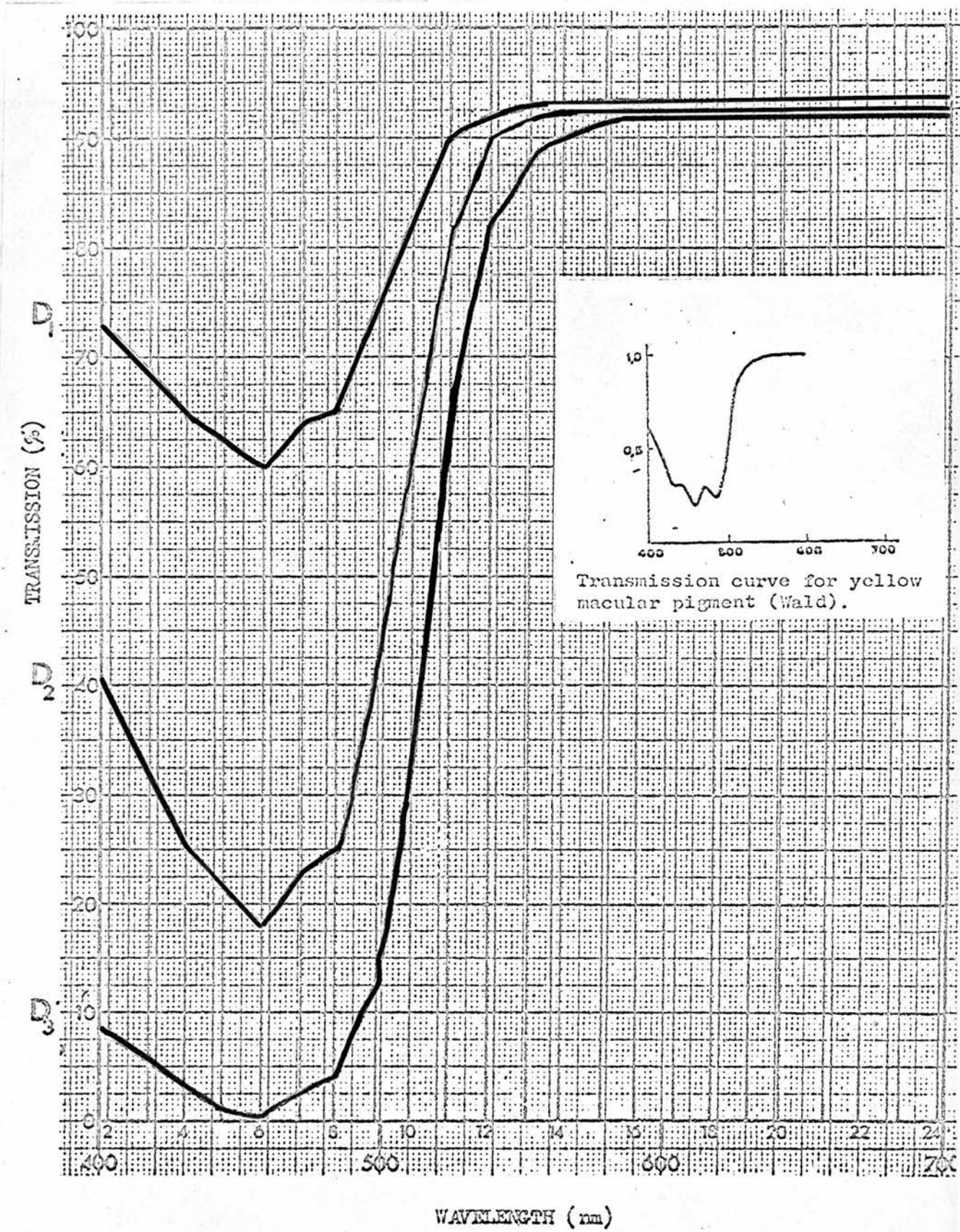


Figure 52 Absorption curves for Xanthophyll filters D_1 D_2 D_3.

were mainly centred in the blue/green and red regions of the test, although in this case the bulge centred on cap 46 was greater than that centred on cap 1. It is evident from both the illumination and the filter studies that there is a close parallel between these experimentally produced errors and those reported in ageing.

Present Studies

a.) Macular Pigmentation

In an attempt to measure the effect of macular pigment density on the 100 hue test, ASPINALL (1968), made up a series of filters containing xanthophyll of different optical densities. The closeness of the transmission curve for xanthophyll to the curve for the yellow macular pigment is shown in Fig. 52 . The filters were placed before young healthy eyes and transmission factors and luminances were made comparable to those in Verriest's study with selective filters.

Twenty subjects with normal vision were selected, ten of whom working in a visual laboratory were familiar with the 100 hue test, and ten further subjects who were new to the test. The photometric curves for the three xanthophyll densities are shown in Fig. 52. Three pairs of quartz lenses were used for the densities D1, D2, D3, of xanthophyll in solution. The Pretema Spectromat FS 2 was used to obtain the ratio Y filter/Y100% under illuminant C for each of the three/

three densities D1, D2, D3. (Y represents the normal luminosity function, see page 68). In order to equate the apparent brightness with those in the VERRIEST, (1963) experiment, two of Verriest's filters were represented on the spectromat oscilloscope by adjusting the potentiometers across the visible spectrum until the peaks of separate impulses coincided with the Verriest transmission curves. The two filters selected were C and E, see Fig. 51 . Y ratios were found under illuminant C for both filters.

The apparent brightness of the 100 hue caps in the Verriest experiment (initial illumination 1850 lux) under filters C and E is:-

For filter C, Yc/Y100 = 0.33 thus reducing the effective illumination from 1850 lux to 617 lux.

For filter E, Ye/Y100 = 0.06 thus reducing the effective illumination from 1850 lux to 111 lux.

For conditions of equal apparent brightness to Verriest's C filter, therefore, we require conditions of testing A1, A2, A3 such that for filter D1, A1 = $617/t_1$; for D2, A2 = $617/t_2$; and for D3, A3 = $617/t_3$.

where t_1 = Y/Y100 for D_1; t_2 = Y/Y100 for D2; and t_3 = Y/Y100 for D3.

Similarily for conditions of equal apparent brightness to Verriest's E filter we require conditions a1, a2, a3 such that for D1, a1 = $111/t_1$; for D2, a2 = $111/t_2$; and for D3, a3 = $111/t_3$; where t_1, t_2, t_3 are/

are defined as above.

There are, therefore:-

(i) Three illumination levels such that the three xanthophyll filters when placed before the eye have equal luminosity values to each other and to filter C, and

(ii) Three illumination levels such that the xanthophyll filters are again equal to each other but now equal to filter E.

Thus there are six conditions of testing made up of three densities of filter combined with two illumination levels. In addition to the six experimental test conditions each subject was given the test without filters under standard test conditions. In order to prevent a systematic practice effect and/or a fatique effect influencing the data, the seven test conditions were randomised across groups. (It should be noted that Verriest did not control these effects and tested each subject in the order of increasing filter density). The practice effect may not influence the experienced group data as subjects in this group have had sufficient contact with the test to reach a plateau in the learning curve. However, fatique effects may still operate. The inexperienced group data may well be influenced by both factors.

Results for the two groups for total error scores are given in Table III.

Table III.

Condition Ao is the normal test condition without filters.

" A1 represents filter D1 at luminosity level ≡ C

" a1 " " D1 " " ≡ E

" A2 " " D2 " " ≡ C

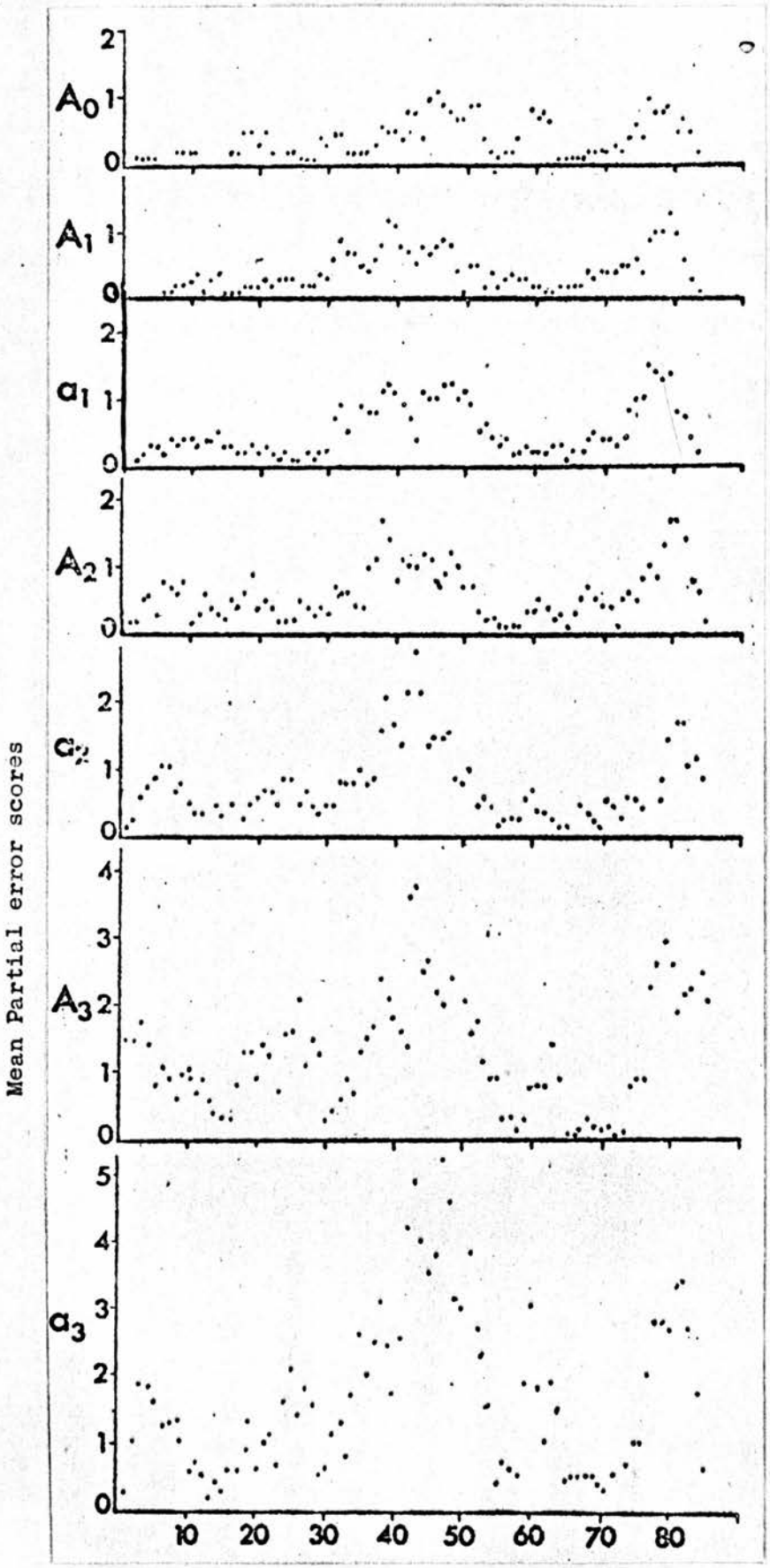
" a2 " " D2 " " ≡ E

" A3 " " D3 " " ≡ C

" a3 " " D3 " " ≡ E

As in the study with yellow filters (VERRIEST, 1963), there is an increase in error score and in the standard deviation of group scores with increase in filter density. In addition, contrary to Verriest's findings, the experienced group did significantly better than the inexperienced group, particularly in condition Ao and A1. Mann - Whitney U tests showed significant differences between the two groups for conditions Ao, A1, a1, A2 and no significant differences for conditions a2, A3 and a3. The last three conditions indicated that the two groups only produced equivalent test scores at low illumination levels or strong filter absorptions. In addition the experienced worker with filter D1 produced a significantly better test scores than the inexperienced worker with no filter. Thus the experienced worker could deal with filter D1 and D2 and produce profiles acceptable for normal colour discrimination. Many of the differences in means under different filter conditions turned out to be significant (Wilcoxon matched pairs/

Figure 53 Group 1 - Inexperienced group scores

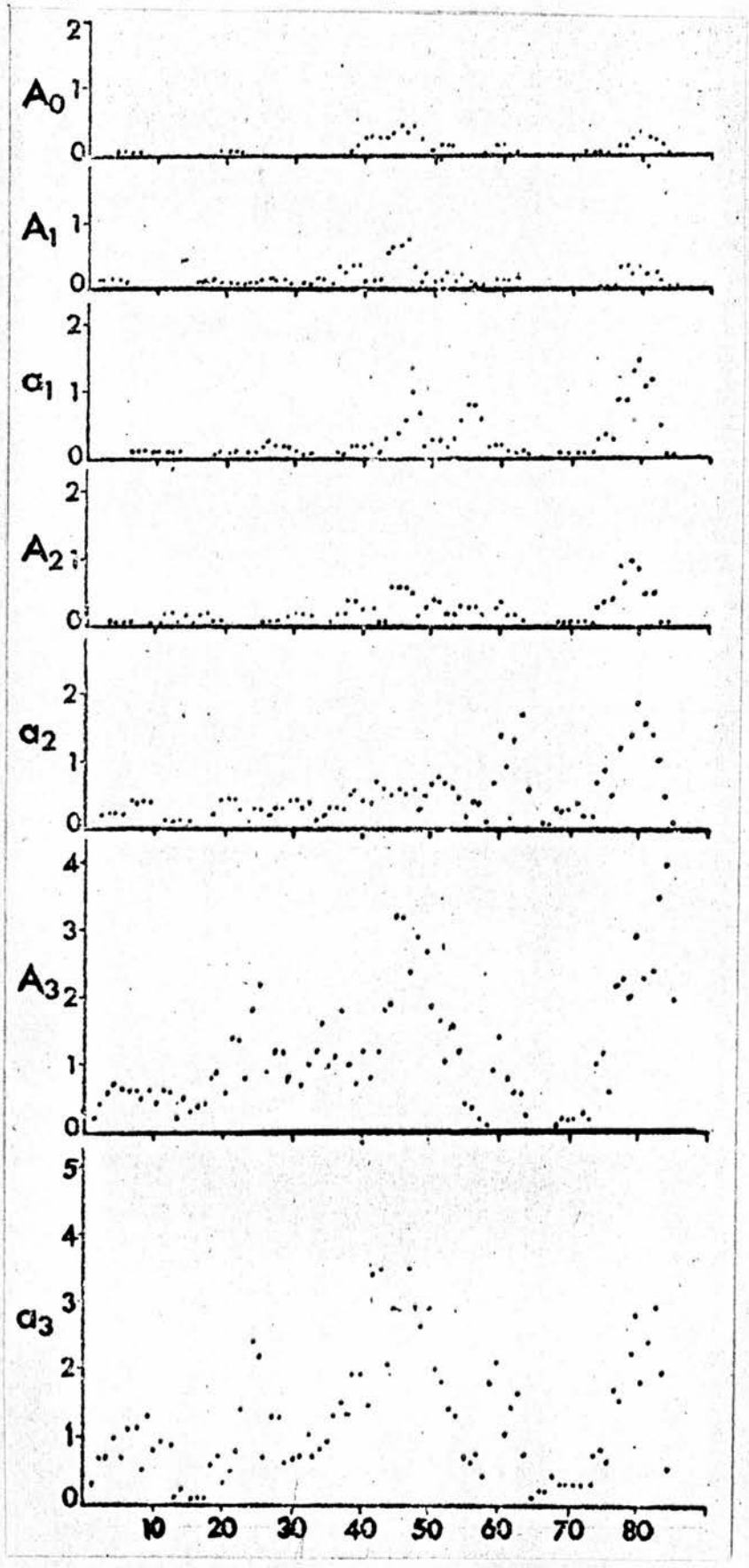


pairs test). This indicated that both groups were affected by the filters. However, the level of error scores for group 2 was consistently lower throughout the series than the error scores of group 1. An explanation of this difference may be that in his familiarity with the original task the experienced subject has learned more than simply the hue ordering of the caps. He may have learned for example the appearance of the total configuration, and also may have learned to appreciate the small brightness differences that exist between certain caps. When the novel task imposed by the filter is presented, thereby impairing hue discrimination, the additional cues may now be at his disposal. Whatever the reason, it is interesting that a non-sensory factor (i.e. familiarity with the task) can produce such significant variations in test scores between two otherwise matched groups.

The mean partial error scores are shown in Figs.53, 54. The build up of errors with increasing densities of xanthophyll is once again in the blue/green and red regions of the test. Considering the results for the inexperienced group we see that for A1, A2 and A3 ($\equiv$ C in luminosity) the most frequent error points are at caps 39, 38 and 42 and at caps 80, 80 and 79 respectively. This represents a rotation of the error axis from that produced by ageing losses which result in peaks centred on caps 45 and caps 1. The peak at/

Figure 54

Group 2 - Experienced Group Scores.



at cap 80 is frequently as large, and occasionally larger, than that for cap 39. The Verriest C filter, for which conditions A1, A2, A3 have equal luminosities, has one peak around cap 45 and a smaller one at cap 82. Thus in comparison with ageing and filter C, there appears to be a slight shift in axis under xanthophyll which is not present for the other two variables.

Secondly, for conditions a1, a2, a3 ($\equiv$ E in luminosity) the peaks in error scores are at caps 44, 43 and 47; and 77, 81 and 82 respectively. This compares with error peaks for filter E at 44 and 82.

If we consider the results for the experienced group, we see that the bulge produced in the blue/green region is similar to both that of the ageing loss and that of the loss under the filters, C and E and centres on cap 45. The greatest difference in this case is that losses in the red region centre around cap 80 which again represents a clockwise shift of error scores from the tritan axis. In this group the errors in the red region are of the same order of magnitude as those in the blue/green region. Thus for this group one of the "wings" forming the axis has shifted, the other has not. On the basis of random sampling errors, if the modal error points for the tritan axis, and age changes are at caps 45 and 1, then for these results to be members of the same population of error scores, we/

we would expect half the means to fall on one side and half on the other side of the tritan axis. On examination, eleven out of the twelve samples under xanthophyll fell on one side of the tritan axis. This represented a significant shift of the error axis ($p < .003$) in a clockwise direction from the tritan axis.

Inspection of the total mean error scores under different viewing conditions showed that for Group 1, the experimental condition which produced an error score under xanthophyll similar to filter C was A1. Filters D2 and D3 produced larger errors scores of 50.9 and 109 respectively. As the apparent luminosities were the same in all cases, the difference in error score must be the result of differences in spectral transmission between the filters. Similarly, the total error score for condition a2 was the same as that obtained under filter E. For equivalent densities of xanthophyll, the error score was always higher at the lower level of illumination (i.e. for E rather than for C). A further analysis using each individual score for each test condition enabled comparisons to be made between the differences in the means for any two test conditions. Thus differences between means were examined for conditions of:-

a.) constant filter absorption characteristics and changes in luminosity./

luminosity.

b.) constant luminosity levels and changes in filter absorption.

There were significant differences for both luminosity and filter absorption changes (Wilcoxon matched pairs test). However, the ratio of significance to non significance was higher for the filter absorption changes. In other words increased filter density was more detrimental to 100 hue performance than reductions in luminosity.

In conclusion there is evidence to suggest that macular pigmentary effects as simulated by xanthophyll, move the error axis clockwise by about five caps from the red and blue/green tritan error area. The shift in axis is a movement towards the tetartanopes confusion axis. This supports the idea that tetartanopia results from a tritanope's confusion with additional abnormal macular pigmentation. Age changes and prereceptoral changes as simulated by the Verriest filter, produced confusion in the tritan test regions with the greatest error score centred around the blue/green caps. However, the magnitude of errors under xanthophyll was of the same order in both red and blue/green test regions. The variability about the mean tended to increase with increasing filter density. In addition subjects making greater than average errors with no filter, tended to make above average errors when wearing filters. There/

There was an indication that selective absorption of certain wavelengths affected test performance more than changes in luminance.

b.) The upper limit of non-random arrangements

A second experiment was carried out to determine the upper limit for non-random sorting in the test. In recent years the test has gained widespread publicity and acceptance as a clinical measure of visual disturbance (COX, 1960; FRANCOIS and VERRIEST, 1961; VERRIEST, 1963; KINNEAR, 1965; LAKOWSKI, 1969). As it's frequency and range of use increase the question of a meaningful upper limit on performance arises. Given that no disproportionate accumulation of errors has arisen in any one test region, the limit of the total error score for normal visual performance is usually the 95th percentile point. This coincides with total errors ranging from 74 - 174 depending on age (see Table II). In clinical studies however, total error scores ranging from normal to well over 1,000 have been reported as valid indices of visual performance for inter and intra individual comparisons. Do such high scores indicate the presence of any colour discrimination? One approach to answering this question is by considering the error scores produced by cap arrangements generated on a random basis. By selecting a criteria for "randomness", scores below criteria can be assumed to result from the operation of at least some visual/

visual function.

For present purposes, random arrangements are considered:-

a.) with reference to any one box of 21 caps, and

b.) with reference to the total error score resulting from the sum of four such boxes.

Random number series were generated by placing 21 caps in a box and drawing them out one at a time, the box being shaken between draws. This method was selected because of its face validity in being precisely the method required in carrying out the test if no colour discrimination was present. Furthermore, its alternative method i.e. use of random number tables has the limitation that certain arrangements e.g. an orderly consecutive series, are suppressed in the construction of random number tables. (SPENCER BROWN, 1957). While the probability of this and similar ordered events is minimal (one over factorial 21), such an arrangement must be considered as a member of the set of possible arrangements.

Forty such arrangements were generated by the method. These 40 were then randomly split into 10 groups, each containing four arrangements. The four arrangements were then transferred to the test situation by adding the constant 21 to the second series; 42 to the third series, and 63 to the fourth series in all groups of four, and the total error score was calculated/

calculated in the usual way. Each arrangement of 21 numbers was then scored with reference to the other three arrangements in its group. This procedure is necessary to obtain the error score for the end caps in a series. For instance, the maximum error possible within any block of 21 occurs when caps numbered 21, 1 and 20 are adjacent. Using the normal scoring system this results in an error for cap 1 of (20 + 19 - 2) or 37. However, the maximum error possible for terminal caps is much greater than this. Consider the second series in the group of four. Here, by means of the transformation, the numbers range from 22 to 43. The terminal caps between series 1 and series 2, now have a maximum score given by a cap arrangement such as 21, 1, 43. This results in an error score of (20 + 42 - 2) or 60. Consequently each series of 21 was scored in this manner so that the random error score should be appropriate for the particular method of scoring used in this test.

The average of a set of random series, indicates the most likely error score associated with a random arrangement. The standard error of the mean indicates the variation likely in this average. The standard deviation indicates the range of error scores which are possible on a random basis. The standard error of a standard deviation indicates the variation likely in the standard deviation./

deviation.

Results for a.) any block of 21 numbers corresponding to any single box in the test are:-

Mean = 294

Standard error = 6.3

Standard deviation = 41

Standard error of the standard deviation = 4.6

Using a 1-tailed test and $p < .01$ as probability level, gives a lower cut off point for the error score per box of 294 - 2.33 x 41 = 200. Therefore, an error score on any box which is greater than 200 can be considered to have arisen from a random arrangement of caps. If any single box is under scrutiny, this is the appropriate criterion score.

It must be emphasised that this does not imply a total error score for four boxes of 800. Such an error score has a probability of occurrence on a random basis of $(.01)^4$ or of one in ten million.

The appropriate figures if the total error score is to be assessed are:-

Mean = 1176

Standard error = 9.1

Standard deviation = 82

Standard error of the standard deviation = 18.2

Using the same criteria as above, this gives a lower cut-off point for the total error score of 1176 - 2.33 x 82 = 984. Scores greater than this/

this can be assumed to result from a random arrangement of caps. Only scores below this level can be assumed to depend upon the operation of visual function. Precisely what is the nature of the function is a separate question. This is not necessarily a criterion point for colour discrimination per se, as is instanced by vision mediated on a scotopic luminosity curve. (Scotopic reflectance factors for the 100 hue caps indicate that brightness cues can be used for an acceptable ordering of boxes two and four. For present purposes only the upper limit imposed by randomness has been considered.)

Particular consideration to this information should be given when:-

a.) the test is used clinically, and

b.) children are tested who may not have a developed concept of serial arrangement.

(iii) Modifications to Test Procedure

It has already been mentioned that a time limit of two minutes was not imposed, and subjects were allowed to continue beyond two minutes providing constructive moves were being made. Furthermore, some subjects had difficulty in understanding the concept of a "regular colour series". The modified instructions following KINNEAR, (1965) were:-

"What I want you to do here is to arrange these caps (pointing) so that they form a regular colour/

TABLE III

Experimental conditions		Inexperienced (Gp. 1) Average age of group 24.6 Mean error score	S.D.	Experienced (Gp. 2) Average age of group 25.4 Mean error score	S.D.
Filter Density ↓	Ao	33.6	24.31	8.4	9.51
	A1	35.7	20.91	14.3	7.33
	a1	44.3	27.58	21.7	10.89
	A2	50.9	34.45	18.0	11.51
	a2	66.8	33.93	40.5	20.63
	A3	109.0	35.84	95.2	44.49
	a3	140.4	49.70	103.9	22.53

Ao represents condition without filter.

TABLE IV

Box 1:	12	17	13	9	21	15	4	18	8	20	6	3	1	10	5	7	19	11	14	2	1
2:	33	41	36	32	34	40	27	24	28	38	25	22	39	23	35	31	26	29	37	42	3
3:	62	48	54	56	61	46	59	55	49	47	50	63	58	52	44	53	57	45	60	51	4
4:	80	66	72	84	77	81	65	59	64	71	67	73	83	74	68	75	70	82	79	76	7

TABLE V

100 hue Presentation for Right Eye/ Left Eye.

Order		Caps	Eye
1.	Box 1	(85-21)	R.E.
2.	Box 4	(64-84)	L.E.
3.	Box 2	(22-42)	R.E.
4.	Box 3	(43-63)	L.E.
5.	Box 4	(64-84)	R.E.
6.	Box 1	(85-21)	L.E.
7.	Box 3	(43-63)	R.E.
8.	Box 2	(22-42)	L.E.

colour series between these two caps (pointing to terminal caps). What colour is this one? (pointing to one terminal cap), and this one? (pointing to the other). What you have to do is arrange them from the bluest (using the colour mentioned by the subject) through the bluey pinks to the pinkest (again using the subjects colour name). The one that is nearest in colour to this one (terminal cap) you put next to it, the one that is nearest to this you put next to it and so on. You can change them around as much as you like. What I am interested in is the final order, when you are quite satisfied that every cap is in its right place in the series. The normal time for a box is two minutes, but I will not take it away from you until you are quite satisfied with the final order."

The other boxes were presented with the comment "I want you to do the same kind of thing with these colours". As the blue to pink box is the easiest, (see page 158) this was presented first.

The test manual instructions suggest that the boxes are rearranged in random order before the test is given again. It was thought that this procedure was not sufficient, as defective subjects are likely to arrange the caps they cannot distinguish in the order in which they are found. The error score in such instances would vary with the randomness of the rearranged caps. As an alternative, a random series was generated/

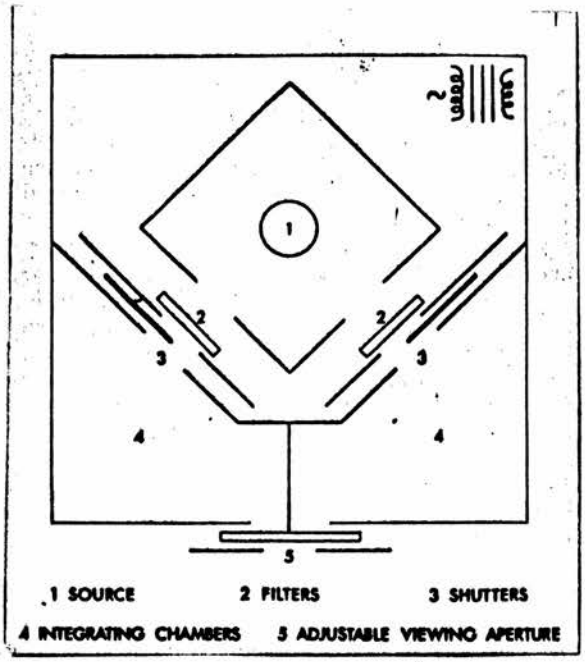


Figure 55 The P-N anomaloscope

generated for each box. After completion of the test, the caps were always rearranged in this fixed random order. The order is given in Table IV.

Finally, as the test was used in predominantly a clinical group, a comparison of test results between right and left eyes for one individual was often of great interest. If the right eye was tested over all boxes, followed by left eye, differences between eyes could occur from practice or fatique effects. To counterbalance these factors a systematic presentation of the boxes was devised as shown in Table V. The test results between eyes could now be compared without the influence of systematic errors.

4. The Pickford Nicholson Anomaloscope

(i) Description of the Instrument

This instrument was designed in 1960, and instructions and norms published by PICKFORD and LAKOWSKI (1960). The instrument is shown in Fig. 55. A deliberate attempt was made in construction to make the instrument as simple as possible from the optical and mechanical points of view. (This ensured that the instrument was sturdy and portable). A single light source (12 v. 48 w.) illuminates each half of the photometric field. Two slide holders each with two filter apertures can be moved vertically across the light path, so that the hue of the light entering the integrating box can be/

TABLE VI

C.I.E. Coordinates and λ_D (nm.) for the Primaries of the Three Colour Equations (P-N Anomaloscope); Measurement by Visual Colorimetry, Illuminant A

Colour mixtures	*C.I.E. coordinates*								
	Primary 1			*Primary 2*			*Standard*		
	x	y	λ_D	x	y	λ_D	x	y	λ_D
Red + green = yellow	0·672	0·309	628·5	0·384	0·550	555·0	0·511	0·446	584·3
Yellow + blue = neutral	0·516	0·458	583·5	0·195	0·152	472·8	0·474	0·412	593·0
Green + blue = blue/green	0·379	0·548	552·5	0·172	0·131	473·3	0·302	0·400	493·5

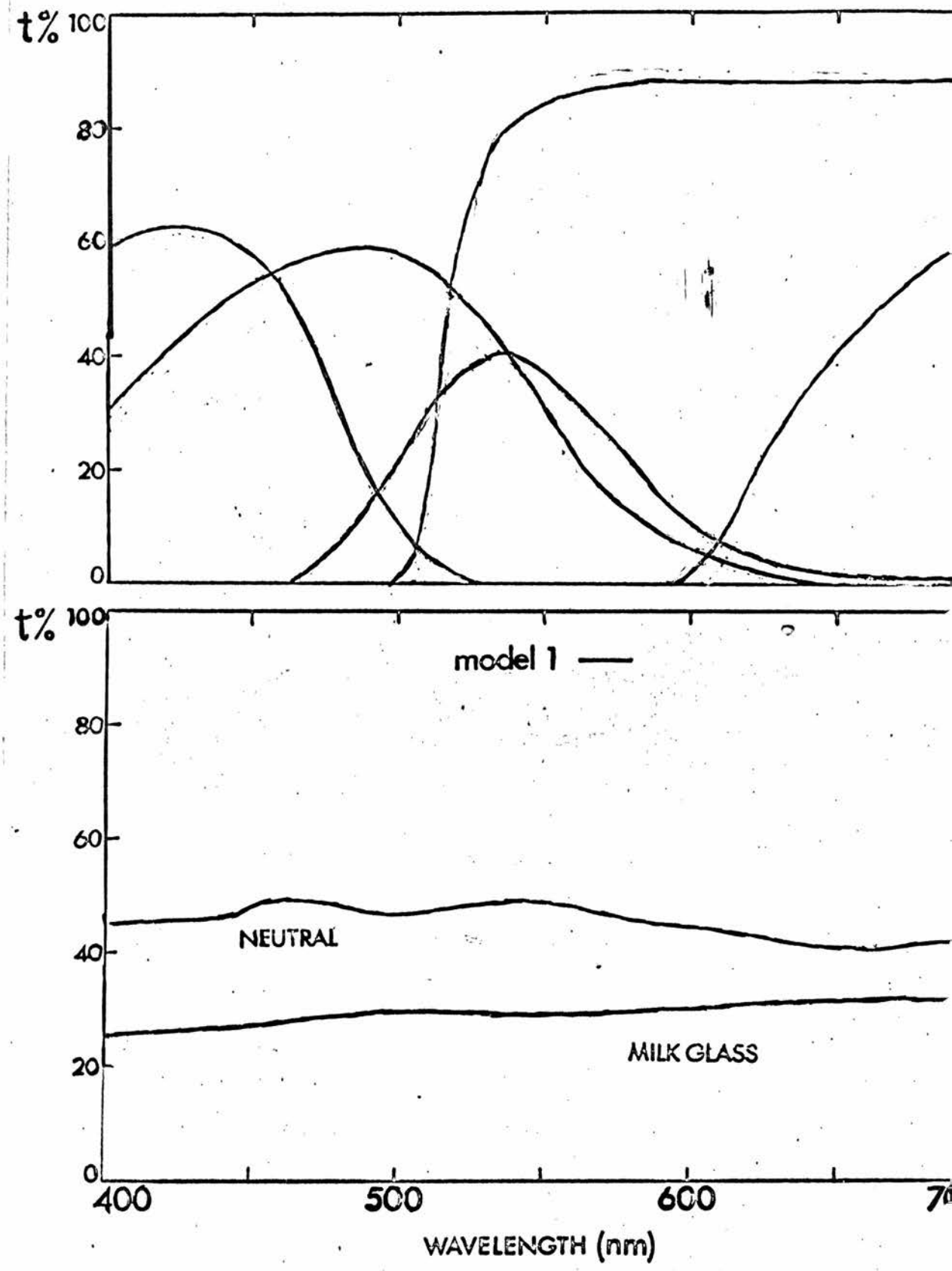
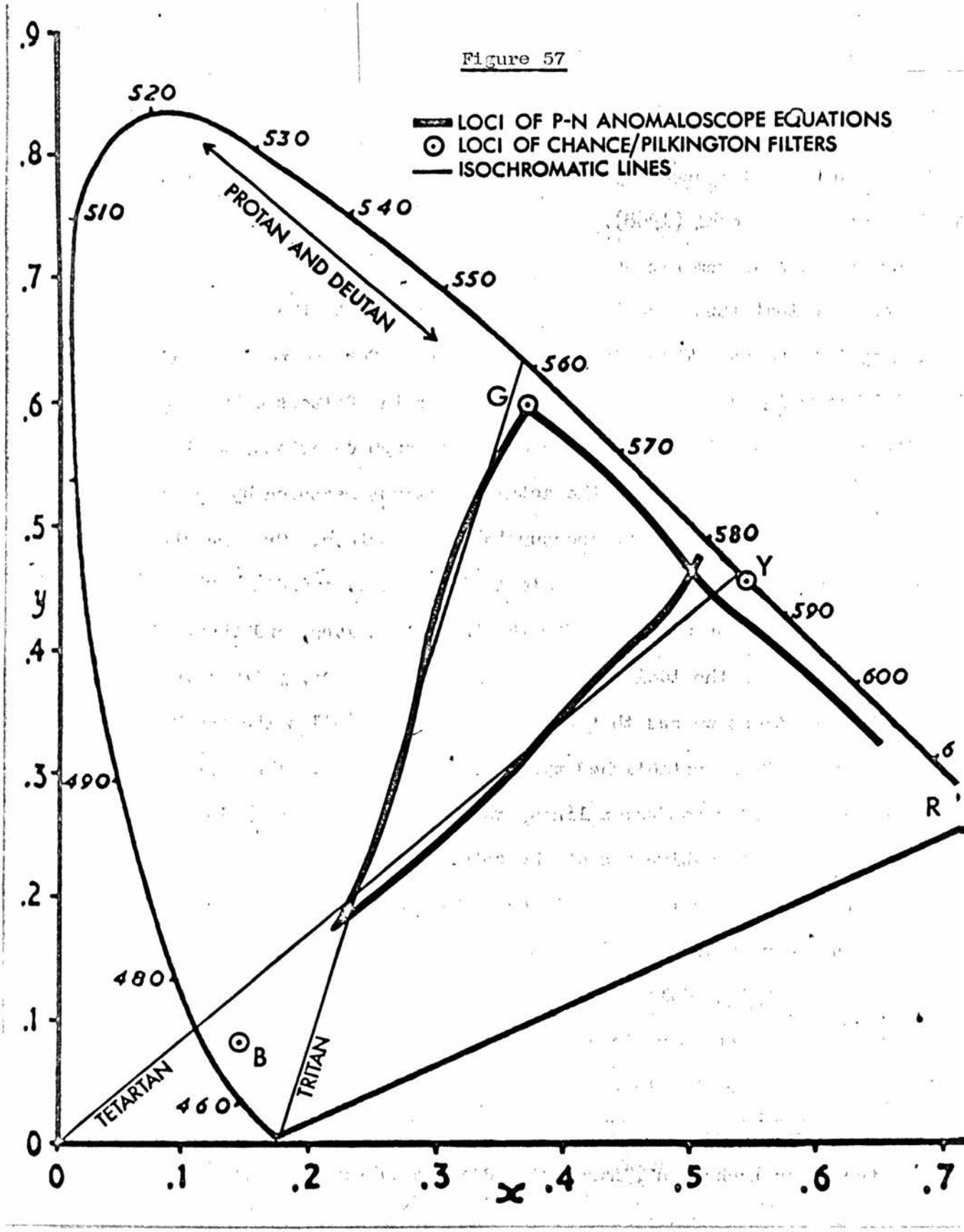


Figure 56 SPECTROPHOTOMETRIC DATA

be changed from the hue of the top filter, through mixed hues, to the hue of the lower filter. The intensity of the light is controlled by a shutter. Both shutter and slide holder are operated from circular dials on top of the instrument, the positions of which are marked on an arbitrary linear scale from zero to 70. A characteristic feature of the instrument is the open viewing situation where the subject views the circular test patch at a distance of one metre. This is particularly useful from the experimental viewpoint as the experimenter can check the photometric field himself for possible instrumental errors. (This is to be contrasted with the telescopic viewing situation which does not have this safeguard and which some patients find difficult.) The integrated light illuminates the viewing aperture which is covered with frosted glass, and a circular stop can be changed to give different angular subtenses at the eye. The angular subtense used in all experiments was 1.5° at one metre distance.

Photometric curves for the Chance-Pilkington glass filters in the instrument are given in Fig. 56, together with their colourimetric data in Table VI. The filters were selected so as to give three colour equations, - red/green, yellow/blue, and green/blue. In the red/green equation, variable amounts of red through to green can be placed in one half of the field, and a standard yellow placed in the other half. In the yellow/blue equation,

Figure 57


LOCI OF P-N ANOMALOSCOPE EQUATIONS
LOCI OF CHANCE/PILKINGTON FILTERS
ISOCHROMATIC LINES
PROTAN AND DEUTAN
520
530
540
550
560
570
580
590
600
510
490
480
460
G
Y
B
R
TETARTAN
TRITAN
y
x
0
.1
.2
.3
.4
.5
.6
.7
.8
.9

equation, variable amounts of yellow through to blue are placed in one half, and a standard neutral white placed in the other half. In the green/blue equation, variable amounts of green through to blue are placed in one half, and a standard turquoise placed in the other half.

The location of three equations in the CIE triangle is shown in Fig. 57. The red/green equation follows the protan and deutan lines, the yellow/blue follows the tetartan lines, and the green/blue follows the tritan isochromatic lines. In theory, all known colour defects can be tested on the anomaloscope in their dichromatic and anomalous trichromatic stages. The retinal illumination level across the different equations is around 70 to 80 trolands and so within the photopic adaptational range. The results in detail are shown in Fig.58 and were measured visually with the Beckstein Universal Photometer, which had provision for colour temperature adjustment of the internal lamp to suit the source to be measured. The abscissa gives the anomaloscope dial units for the variable field and the standard, and the ordinate gives the luminosity values.

The purpose of the instrument is to obtain metameric matches between the two halves of the circular photometric field on all three equations. To do this, the left hand side of the field is changed in intensity only,/

PHOTOMETRIC DATA FOR THE P-N ANOMALOSCOPE

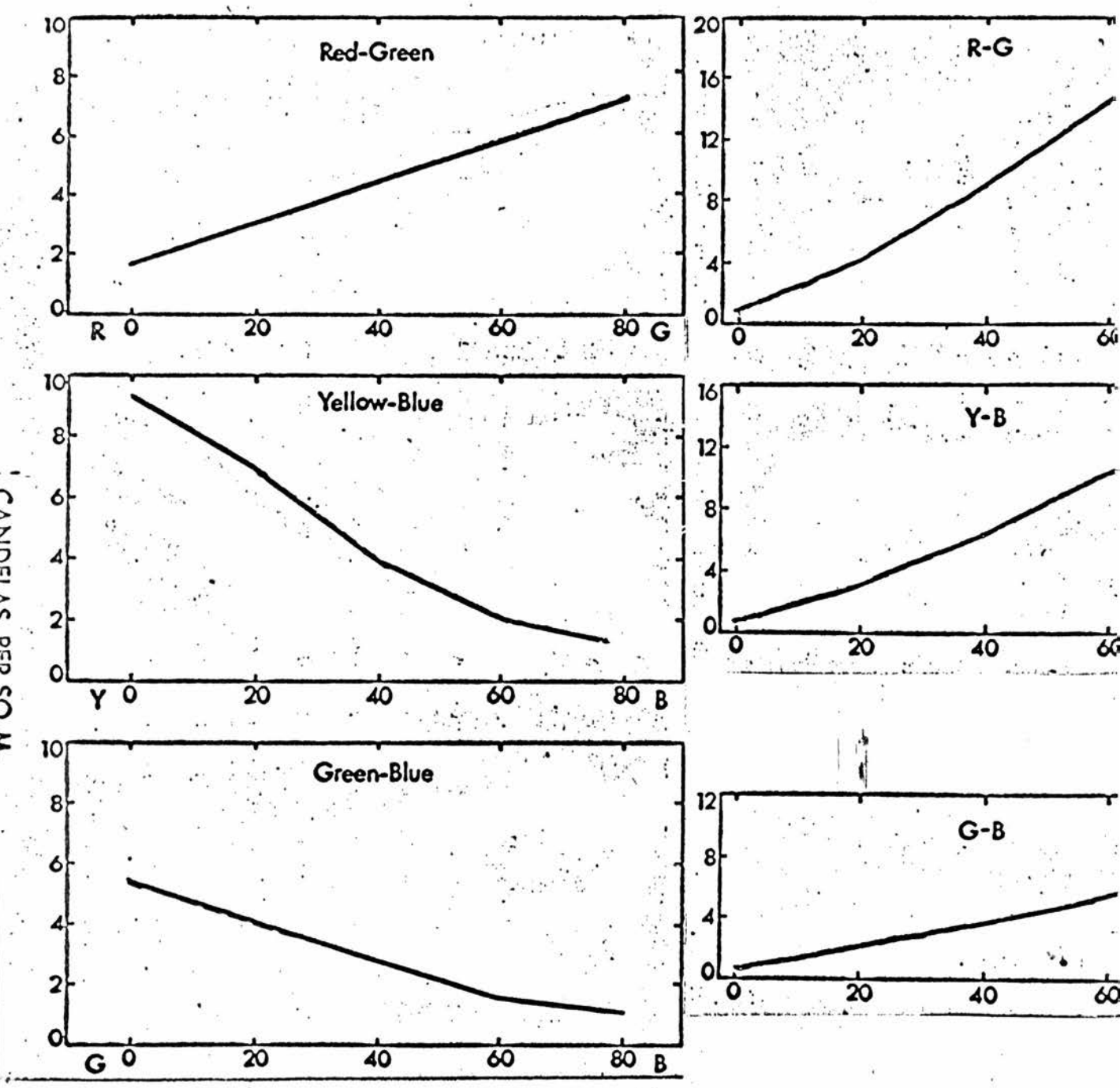
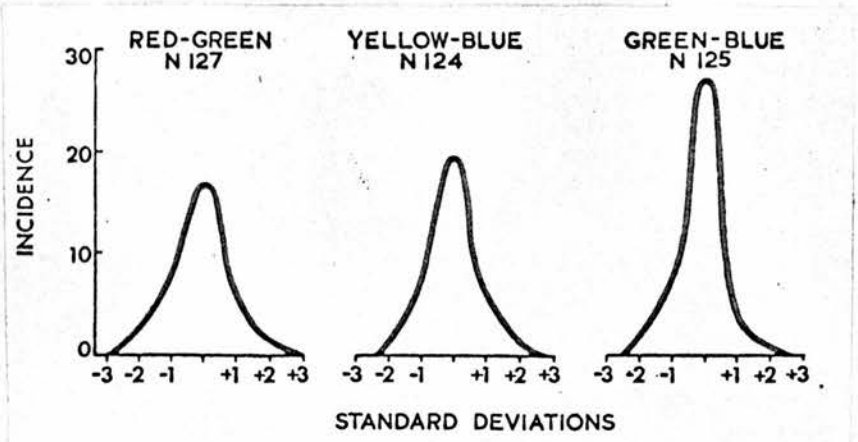


Figure 58

only, while the right hand field is changed only in hue. The standard colour was chosen so that its position in the CIE triangle lay on a straight line between the positions of the two colours in the mixture. The technique of examination is to find the number of variable hue settings of the right hand field which will match the standard settings of the left hand field. Several psychophysical methods are available towards this end. The method of average error can be used so that the subject controls the dial instruments himself. However, PICKFORD (1951) recommends the use of the method of limits, where the examiner makes a number of serial adjustments until he has established all possible mixture ratios which are accepted as matching the standard. (For a discussion of alternative methods of testing, see page 9).

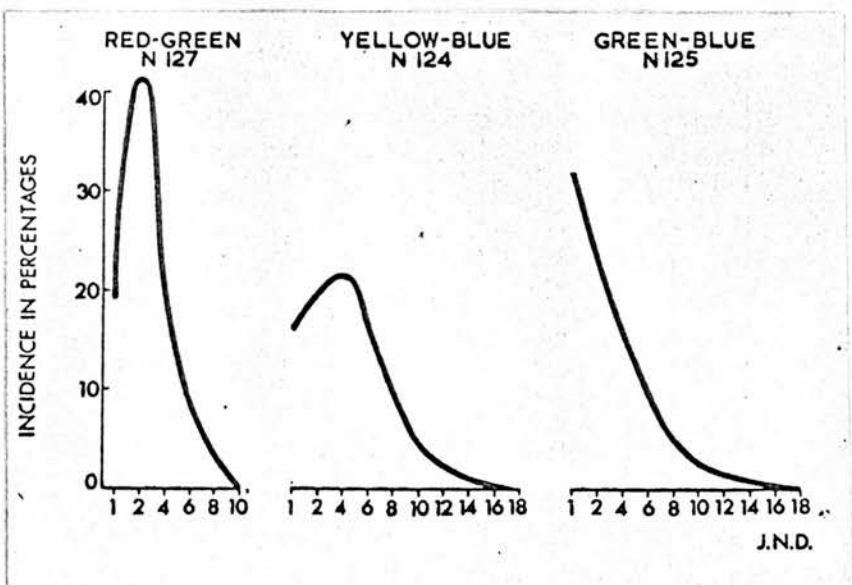
The principle measurements of interest are the matching range (MR), and the mid-matching point (MMP), which is located at the centre of the matching range. There are several ways of recording the data. The anomaly quotient, which expresses the MMP for an individual relative to that for the normal observer is a frequently used procedure. However, statistical methods would appear better suited to deal with individual variations and Pickford has used this approach to relate individual scores to population scores. These methods are particularly applicable when/

DISCRIMINATION MATCHING RANGES



Frequency distribution of mixture ratios for three P-N anomaloscope equations (red-green, yellow-blue, and green-blue) and number of subjects involved (age span 16-60 years).

MID-MATCHING POINTS



Frequency distribution of matching ranges (discrimination) for three equations plotted against j.n.d. scale.

Figure 59

when the distribution of the populations scores is normal, which is true for the distribution of mid-matching points, but is not true for the distribution of matching ranges (See Fig. 59). The individual variations in the MMP, expressed in statistical terms, form the basis of Pickford's classification of colour defects. Subjects with MMP's outside $\pm 2\sigma$ from the mean of the normal distribution he calls deviant (either red deviant or green deviant). The limits to normality he sets at $\pm 3\sigma$. Outside this lie the anomalous trichromats (See Fig. 60). The non-normality of the distribution of matching ranges within a population (the distribution is positively skewed or J shaped, Fig. 59) is handled statistically by use of percentile scores. The 95th percentile will be used as the criterion of normality for all age groups.

Some evidence exists on the reliability and validity of the instrument. Concerning validity, GREEN (1962) has shown agreement between the classification of colour defects on the Pickford Nicholson (P-N) anomaloscope and the Nagel. This is an extremely important finding as the Nagel has proved to be a most efficient and valid means of assessing defective vision (WILLIS and FARNSWORTH, 1952). Lakowski has also shown that the instrument is a valid measure as compared with the König-Helmholtz colour mixer. Subjects with the smallest anomaloscope matching range had the best wavelength discrimination on the/

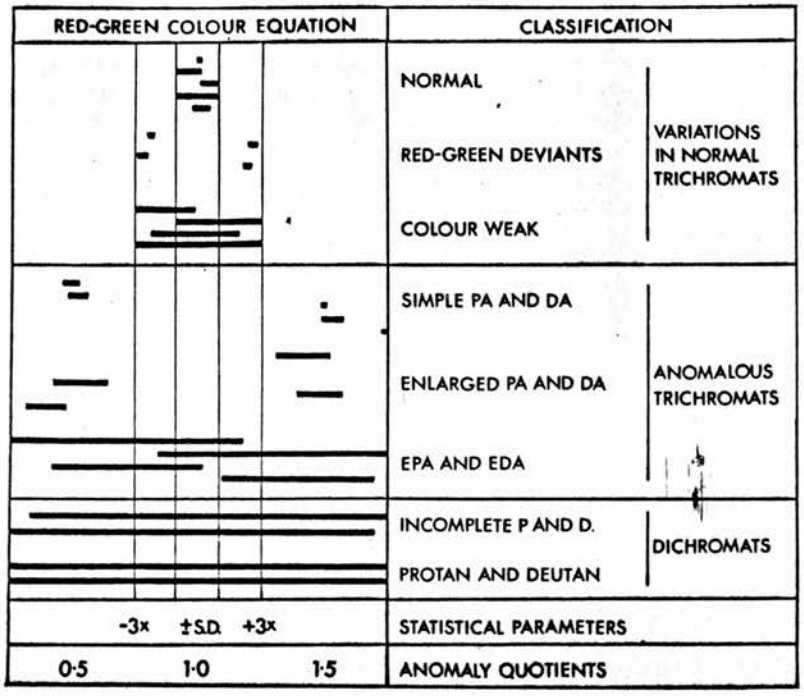


Figure 60 **Graphical representation of red-green colour vision classifications yielded by anomaloscope data (see text for fuller description).**

the colour mixer and vice versa. Similarly, the instruments showed close agreement between the performance of colour defective subjects. The reliability of the instrument has not been extensively studied. However, high correlations have been found between right and left eyes (LAKOWSKI, 1968); in diabetics tested over long intervals, (KINNEAR, 1965); and in colour defective subjects (LAKOWSKI, 1965; ADAM, 1967).

(ii) Norms and the Transformation of the Anomaloscope Scale

Norms for the anomaloscope have been established by PICKFORD and LAKOWSKI (1960) and LAKOWSKI (1964). The extensive studies with this instrument on age and colour vision have been referred to on page 126. Lakowski found the MMP to be exceptionally stable over age, showing no age variation except in the very young, where the MMP in the red/green equation was shifted significantly to the red end of the spectrum. (Displacements of the MMP to the green with increased age have been reported BOLES-CARENINI, 1954). The standard deviation of mixture ratios was larger in the very young and in the very old than in the 20-30 year age group. On the other hand the matching range was particularly sensitive to age changes. This estimate of colour discrimination showed the red/green equation to be least affected by age, with significant differences only appearing over the age of 55 years. However, the/

the yellow/blue and green/blue equations began to show an extension of the MR at 30 years of age.

The norms used in this study are based on the data of Lakowski. However, they are presented in this report in a different form. The explanation for this change rests on the non-linearity of the visual scale as recorded in anomaloscope arbitrary units. In fact, the anomaloscope scale only gives an indication of the position of the filter in the light path, and has no relevance to visual discrimination. Thus points within an equation or between equations cannot be compared on a visual basis. However, it is often necessary for diagnostic purposes to compare for example red/green colour discrimination with yellow/blue discrimination. Koellner's rule (see page 108) is a particular instance where this comparison is required. What is not discussed is the basis or the grounds on which this comparison of red/green and yellow/blue vision, (two different entities) is to be made. There would appear to be two possible ways of making the comparison. One solution would be to transform each anomaloscope equation onto a common linear scale so that points within an equation and between equations can be directly compared. The second solution, which is statistically based, involves computing the mean and the standard deviation of red/green discrimination, and the mean and standard deviation of yellow/blue/

blue discrimination in the population. Any individual can then be placed in terms of the number of standard deviations he is away from the mean (Z scores) on both the red/green (rg) and the yellow/blue (yb) measure. The relationship between the Z scores (e.g. expressed as Zrg - Zyb) gives the comparison of red/green to yellow/blue discrimination for that individual. However, this latter solution still maintains red/green and yellow/blue vision as two different entities, but uses the individual's place in relation to the population distribution of each entity as a means of comparison.

It is apparent that a solution which unites the two measures on a common scale is preferable. Consequently an attempt was made to transform the scale into a linear one and so provide a more meaningful basis for the measure of visual discrimination.

Scale Transformation

Equal intervals on the anomaloscope arbitrary scale do not correspond to uniform shifts in dominant wavelength λD. For example in the red/green equation, a shift of 15 arbitrary units in each direction from the normal MMP represents shifts of 12.75 nm. and 7.75 nm, respectively. The position of the anomaloscope equations in the CIE system is seen in Fig. 57. It has already been mentioned (page 89) that equal distances in the CIE triangle do not represent equal visual distances. The clearest indication of this is shown by the MacAdam/

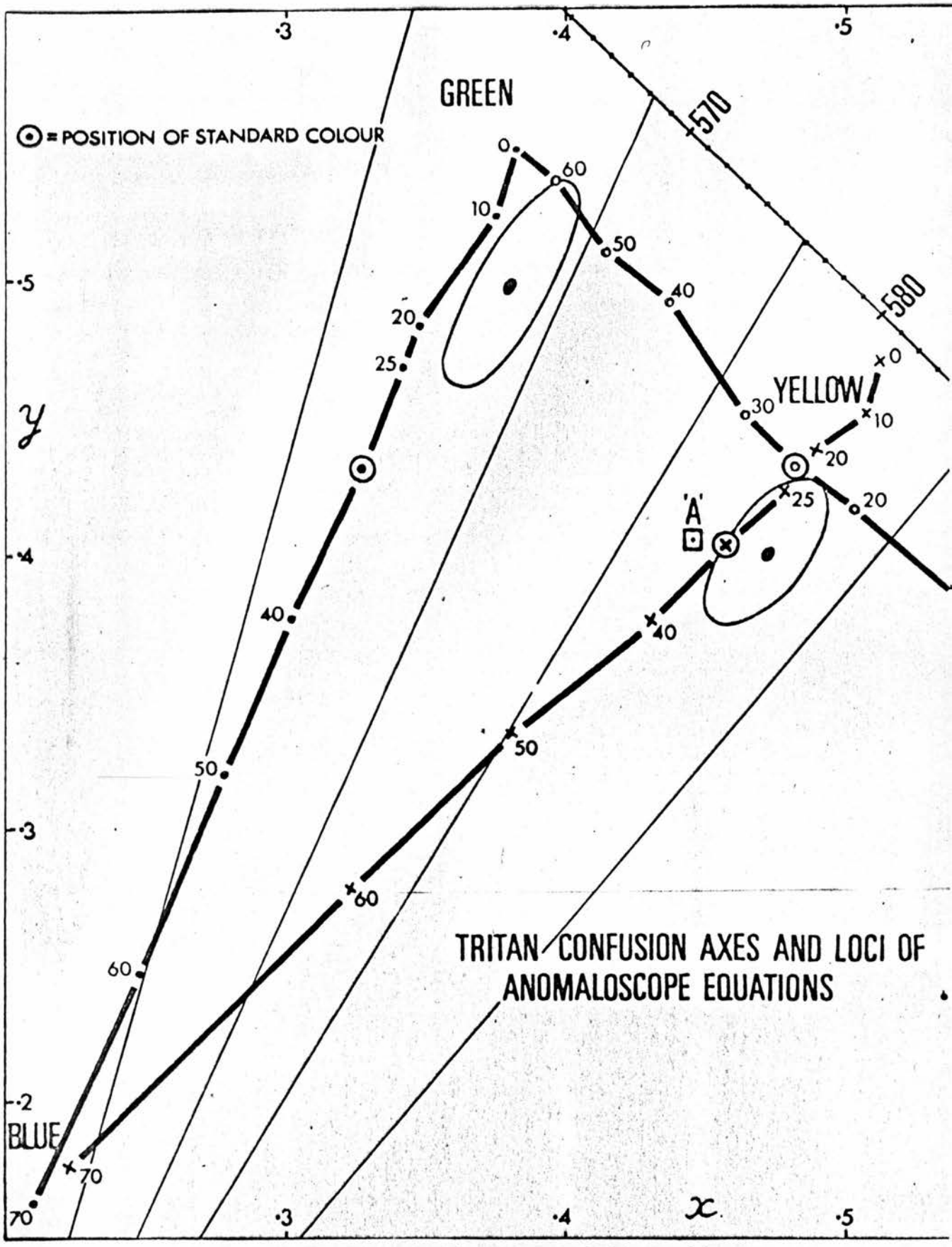

GREEN
⊙ = POSITION OF STANDARD COLOUR
570
580
YELLOW
'A'
BLUE
y
x
·3
·4
·5
·2
0
10
20
25
30
40
50
60
70
TRITAN CONFUSION AXES AND LOCI OF ANOMALOSCOPE EQUATIONS

Figure 61

MacAdam ellipses which, by determination of the difference thresholds at constant luminance, represent the area of colour confusion around a particular colour in CIE space. The ellipses have their major axes pointing towards the blue corner of the colour triangle. Two such ellipses are plotted in Fig.61 after KINNEAR (1965). They show that the yellow/blue and green/blue equations lie along a direction of least sensitivity, while the red/green equation lies along that of greatest sensitivity.

The problem is to select a transformation so that the ellipses are changed into circles of approximately equal size. Thus at any point in the colour triangle, a given physical distance between two points is comparable with a visual difference, independent of the position in CIE space or of the orientation of the line joining the two points. Because it is advantageous to preserve certain properties of the colour triangle, e.g. the additive colour mixture rule and the confusion loci of dichromats which are straight lines, the selected transformation must be linear. Although, no linear transformation will give a perfect solution (colour space is thought to be Riemannian after the data of MacAdam) a practical compromise can be reached giving a considerable improvement on the CIE triangle. There are two parts to the solution:-

a.) to select the transformation/

transformation.

b.) to define a just noticeable difference (j.n.d.) within the new transformed system.

Of the two parts, the solution to a.) was the more important for practical purposes. Once the visual scale was linear, relative comparisons between normal and defective vision could take place. The absolute size of the j.n.d. was not so important in the present context, as relative comparisons were the main concern. However, in order to give the j.n.d. some semblance of reality, JUDD's (1935) data was used as the unit for the new scale.

The anomaloscope equations were measured visually be means of the Lovibond-Schofield Tintometer. (Readings from the Tintometer can be expressed in chromaticity co-ordinates of the CIE, so that each anomaloscope arbitrary unit can be expressed as a point in the CIE system). Several uniform chromaticity spaces (UCS) have been proposed, and the ones considered were Judd's, Farnsworth's, the CIE 1960 UCS and Simon-Goodwin charts- see BOUMA (1972). In each uniform chromaticity space the MacAdam ellipses were plotted at different locations in the space; a fixed number of Judd's j.n.d. units were drawn in the space at different positions; and Wright's wavelength discrimination steps were drawn. The best approximation to UCS (i.e. the MacAdam ellipses became similar sized circles in different regions, and/

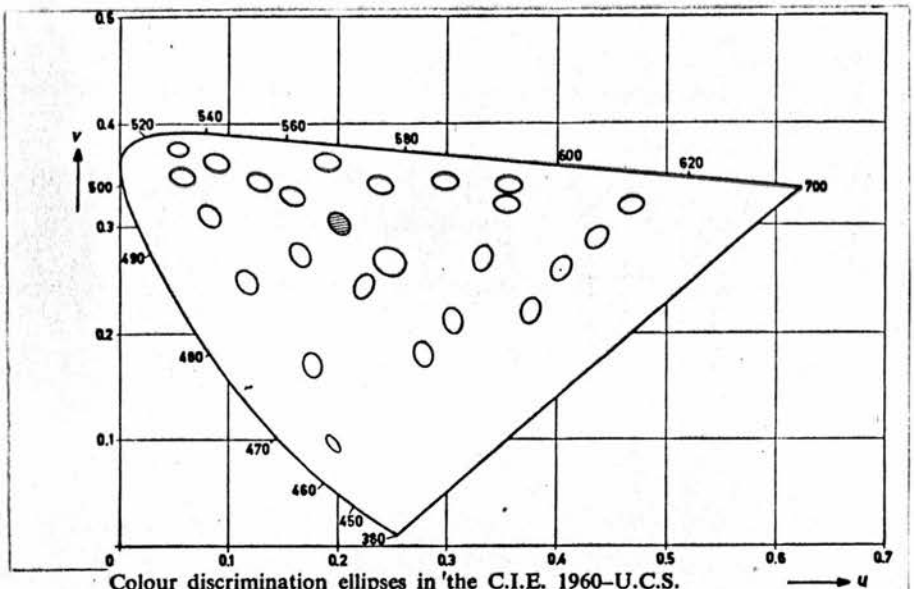


Figure 62

Colour discrimination ellipses in the C.I.E. 1960–U.C.S. diagram, calculated by STILES from the results of his measurements of liminal increments. Colours represented on the ellipses are separated by three limens from the central point.

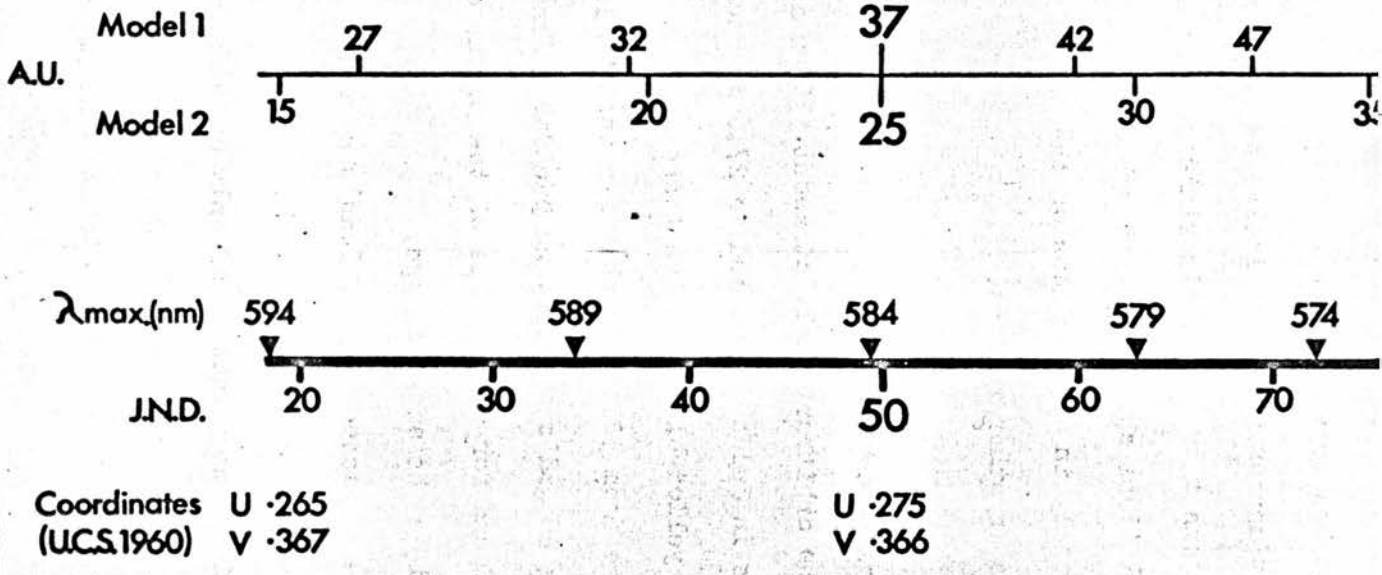


Figure 63

and lines of a fixed number of j.n.d.'s at different orientations were of the same physical length) was the Simon-Goodwin charts. However, because the colour space in the Simon-Goodwin charts is divided into so many different areas, the anomaloscope data was found difficult to handle on this system. The remaining spaces all had points in their favour, and all approached UCS in different areas of the CIE triangle.

The final choice was the CIE 1960 UCS (uv space) space, which transformed the ellipses into comparably sized circles, in those areas of the triangle where the anomaloscope equations lay. The equations for this transformation were:-

$$u = \frac{4x}{-2x + 12y + 3} \quad ; \qquad v = \frac{6y}{-2x + 12y + 3}$$

and the transformation is illustrated in Fig. 62. Finally, this particular space has recently received approval from the CIE Committee as a recommended standard uniform chromaticity space.

In the selection of the UCS itself all that was necessary was to plot lines, of e.g. 30 j.n.d.'s, on to the different spaces and to compare their physical lengths for equality. The second part of the problem was to define the j.n.d. unit itself. The data of Judd, MacAdam, Stiles, Wright, Brown and Perry were considered (See JUDD, 1959). It was apparent that different studies had used different matching and surround conditions,/

conditions, and different luminance levels to define their j.n.d.'s. In addition the results were standardised on different numbers of observers. MacAdam ellipses, while in general use, represented the discrimination of only one observer. Again certain surround conditions appeared inapplicable to the anomaloscope data. The final choice of unit was Judd's, as this resulted from the most comprehensive study involving about thirty observers. Comparisons of the Judd and MacAdam units showed that for example:-

1. On the red/green equation a distance of from 50 to 70 arbitrary units at 570 nm. was equivalent to 27 units in Judd's j.n.d.'s and to 27.6 units in MacAdam. ellipses.
2. On the yellow/blue equation the distance from 30 to 60 arbitrary units was equal to 28 Judd j.n.d.'s and 21 MacAdam ellipses.

Similar calculations showed discrepancies at other parts of the colour space relevant to the anomaloscope equations.

Now that the colour space and unit had been chosen, the earlier age studies (LAKOWSKI, 1964) could be transferred to the new system. The calculations were as follows. Firstly, the anomaloscope data was converted from (xy) co-ordinates to (uv) co-ordinates by computer, and then plotted in (uv) space. The locations of illuminant 'A' and 'C' were plotted in this space with/

TABLE VII

ANOMALOSCOPE j.n.d. SYSTEM (u.v. TRANSFORMATION USING JUDD's j.n.d.'s)

ARBITRARY ANOMALOSCOPE UNITS WITH THEIR TRANSFORMED j.n.d. UNITS IN BRACKETS

R-G equation

0	3	5	8	10	11	12	13	14	15	16	17	18
(-45)	(-35)	(-25)	(-10)	(0)	(4)	(7)	(11)	(14)	(18)	(21)	(24)	(27)

20	21	22	23	24	25	26	27	28	29	30	31	32
(36)	(39)	(43)	(46)	(48)	(50)	(52)	(55)	(57)	(60)	(63)	(65)	(67)

34	35	36	37	38	39	40	41	42	43	44	45	46
(73)	(75)	(77)	(78)	(79)	(81)	(82)	(84)	(85)	(87)	(88)	(90)	(91)

48	49	50	51	52	53	54	55	56	57	58	59	60
(93)	(94)	(96)	(97)	(98)	(99)	(100)	(101)	(102)	(103)	(104)	(105)	(106)

62	63	64	65	66	67	68	69	70
(108)	(109)	(110)	(111)	(112)	(113)	(113)	(114)	(114)

Y-B equation

0	1	2	3	4	5	6	7	8	9	10	11	12
(33)	(34)	(34)	(35)	(35)	(36)	(36)	(37)	(37)	(37)	(38)	(38)	(38)

14	15	16	17	18	19	20	21	22	23	24	25	26
(39)	(40)	(40)	(41)	(41)	(42)	(42)	(43)	(44)	(44)	(45)	(46)	(46)

28	29	30	31	32	33	34	35	36	37	38	39	40
(48)	(49)	(49)	(50)	(51)	(52)	(53)	(54)	(55)	(56)	(57)	(58)	(59)

42	43	44	45	46	47	48	49	50	51	52	53	54
(62)	(64)	(66)	(67)	(69)	(70)	(72)	(74)	(75)	(77)	(78)	(80)	(82)

56	57	58	59	60	61	62	63	64	65	66	67	68
(85)	(86)	(88)	(90)	(92)	(95)	(99)	(102)	(105)	(109)	(112)	(115)	(119)

70
(126)

G-B equation

0	1	2	3	4	5	6	7	8	9	10	11	12
(29)	(29)	(30)	(30)	(31)	(31)	(31)	(32)	(32)	(33)	(33)	(34)	(34)

14	15	16	17	18	19	20	21	22	23	24	25	26
(36)	(37)	(37)	(38)	(38)	(39)	(40)	(41)	(41)	(42)	(43)	(44)	(44)

28	29	30	31	32	33	34	35	36	37	38	39	40
(46)	(47)	(48)	(49)	(50)	(51)	(52)	(54)	(55)	(57)	(58)	(59)	(61)

42	43	44	45	46	47	48	49	50	51	52	53	54
(63)	(64)	(65)	(67)	(69)	(70)	(71)	(72)	(74)	(76)	(78)	(81)	(83)

56	57	58	59	60	61	62	63	64	65	66	67	68
(88)	(89)	(90)	(92)	(95)	(97)	(100)	(102)	(104)	(107)	(109)	(111)	(114)

70
(120)

with the spectrum locus from 565 to 595 nm. The number of j.n.d.'s between 565 and 595 nm. was known from Judd's UCS and this was used as the basis of the red/green equation. For the yellow/blue and the green/blue equations the basis was the number of j.n.d.'s from illuminant C to 580 nm. and from illuminant C to 570 nm. respectively. Finally, the new scale was anchored at the modal anomaloscope setting of the mid-matching point for a normal population, which is stable with age beyond 20 years. This point has arbitrarly been put equal to 50 on the new scale.

Some of the advantages of the transformation can be seen in Fig. 63 where two anomaloscope models with different scales have been transformed to the same system, so that studies on different instruments can be compared. Table VII presents the same data in a more manageable form. The Table is used in the following way. Arbitrary units at the end points of the matching range are first transformed to the j.n.d. scale. This gives the number of j.n.d.'s in the matching range. The half way point between the new end points is used to denote the MMP (Model 2 is the anomaloscope used in this study). The new system allows proper weighting to be given to the minor deviations in colour mixture ratios and to the larger deviations of the anomalous trichromats. Perhaps the most important aspect is in the results of acquired dyschromatopsias, which when transformed to the new/

T A B L E VIII

N	AGE	R - G Mean		Y - B Mean		G - B Mean	
36	13 - 15	44.0	2.9	49.2	2.2	50.1	1.9
56	16 - 25	49.3	3.4	49.8	2.3	48.8	6.8
33	26 - 35	49.3	2.8	49.7	2.5	49.4	2.7
24	36 - 45	49.7	2.1	50.1	1.8	49.7	1.4
14	46 +	50.4	1.4	49.9	4.3	50.4	2.8
	TOTAL	49.5	2.9	49.5	2.6	49.3	4.8

ANOMALOSCOPE MID MATCHING POINTS

Age variations in j.n.d.s.

new system can be meaningfully evaluated against norms for the normal population.

The mid-matching points are shown in Fig.59 and the matching ranges in Fig. 59 . The abscissas are in j.n.d.'s in both cases. The data is also presented in Tables VIII and IX . As the mid-matching point is 50 for a normal population, and as its distribution is normal (Fig.59), the means and standard deviations are sufficient to describe the individual differences. (Note that the red/green equation shift towards the red is significant in the teenage group). The matching range curves, however, are clearly skewed so that Table IX includes other statistical parameters to describe the population. The deterioration in discrimination with age is clearly seen in Table IX . The transformation to the j.n.d. scale shows that while losses occur on all equations they are greatest in the yellow/blue and green/blue regions. Tables VIII and IX will form the basis for all anomaloscope comparisons in the clinical group.

For the colour defective subject, the anomalous trichromats, Protanomalous (PA) and Deuteranomalous (DA) now have their mid-matching points at approximately the same distance from the modal setting of the normal population. The dichromats, (protans and deutans) are unaffected by the transformation as they match all/

TABLE IX

PARAMETERS		Apprentices 13-15 N = 36	AGE - GROUPS 16-25 N =56	26-35 N = 33	36-45 N = 24	46+ N = 14	TOTAL N = 127
R-G	Mean	5.5	3.2	2.8	3.0	3.6	3.1
	Mode	1	2	2	2	2	2
	Median	5.0	2.0	2.0	1.8	3.0	2.0
	% 25th		1.5	1.5	1.0	1.2	1.3
	75th		4.0	3.5	4.0	4.0	4.0
	95th		7.0	6.8	7.0	8.0	7.0
Y-B	Mean	7.6	4.1	5.9	7.0	11.1	6.0
	Mode	1.0	1.0	2.8 & 8.7	5.0	5.0	4.5
	Median	3.0	3.0	5.5	5.0	7.0	4.5
	% 25th		1.0	2.5	3.5	4.5	2.0
	75th		6.0	7.5	8.0	16	7.5
	95th		9.5	12.5	18.0	23.0	15.0
G-B	Mean	6.4	3.5	5.3	6.0	11.0	5.4
	Mode	2.0	1.0	1 & 6.5	1.0	2.0	1.0
	Median	5.0	1.75	4	3	7	2.5
	% 25th		0.5	1.0	1.0	1.2	1.0
	75th		5.0	6.5	6.5	16.5	6.5
	95th		9.0	13.5	16.0	31.5	17.5

ANOMALOSCOPE MATCHING RANGES

Age variation in j.n.d.s

all colours across the equations. However, in these cases it is the brightness variable which determines the classification particularly at the red end of the equation. Here Lakowski found no overlap between the brightness settings of deutans and protans.

(iii) Test Procedure

The skill in testing rests on the control of the intensity variable at different settings of the mixture ratio, so that the judgement of the patient is based on hue differences alone. The photometric field is presented at the MMP of the normal population. This is the mixture ratio which is most likely to be accepted. (In clinical groups a widening of the matching range about the normal mid-matching point is frequently found). The mixture ratio is changed in one direction from the MMP until a difference between the two halves of the field is detected. The instrument is then reset and changes are made in the other direction away from the MMP along the equation. The two end points define the matching range. The smaller this is, the better is the subject's discrimination.

In addition to the quantatative measurement of the matching range there are several qualitative observations which give the experimenter an indication of the subject's colour ability. Some patients found that the colours faded as they looked at the field and merged into each other. To counteract this, the field was/

was frequently interupted by the experimenter placing his hand over it. This was done while mixture ratios were altered, and also when the patient had looked for longer than ten seconds at the photometric field without giving an adequate response. Subjects with poor discrimination tended to be inconsistent about the end points of the matching ranges. They were also poorer in describing why the colours did not match when asked to do so. It is necessary to ask subjects this question to avoid discriminations on the brightness variable alone. If one half of the photometric field was described as darker than the other half, the brightness variable was first adjusted. If a difference still persisted when the two fields were equally bright, patients were asked to describe the nature of the difference.

The initial instructions given to the patient are based on LAKOWSKI (1964) and KINNEAR's (1965) methods of testing developed after years of experience with the instrument. This method of testing is as follows. The two halves of the photometric field are set to approximately the normal MMP. The subject is then told:-

"You see this dark line (pointing to the division between the two sides of the field). This is a fixed division which is always present. I can shine a light into either side of it. What I want you to do is to/

to tell me when the two sides are the same brightness and the same colour. I can make one side dark (darkening the left side) or the other side dark (lightening the left side), and I can also change the colours of either side. (This is NOT demonstrated). All you have to do is to tell me what is wrong and I will move the dials until we get the same all over, the same colour and the same brightness, which we will call matching. What is wrong now? (the left side is still too bright)." The brightness is readjusted and a check made of the visual equality. A new mixture ratio is selected and the process repeated. The photometric curves in Fig.58 illustrated a gradual brightness change across all equations. Subsequent change of the mixture ratio does incorporate a change in brightness, and it is necessary to compensate for this before a colour match can be accepted. The end point of the matching range is reached when no variation in the brightness variable will equate the two fields. This point is repeated once or twice and the value noted. The procedure is repeated to determine the other end point of the matching range.

The method of limits has been assessed in Section II, and the response criterion changes discussed in that section and in the studies of colour vision and age (page 129). These observations are relevant to the determination of the end points of the matching range. For instance, once/

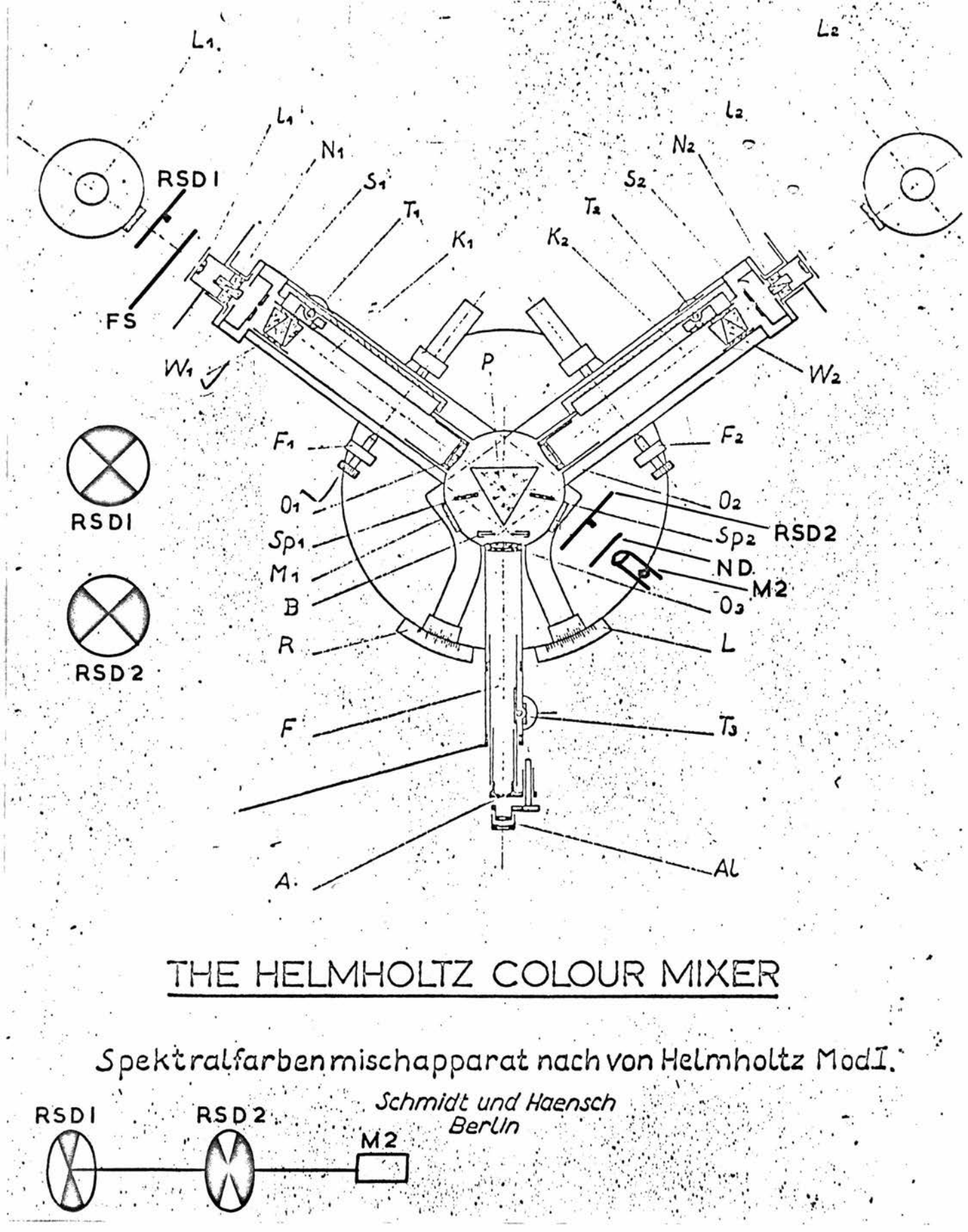
once the difference between the fields has been noticed (the subject is no longer uncertain about the type of colour change but now knows what to expect) the end point is moved nearer to the MMP and the matching range made slightly smaller. Similarly some observers when asked whether the fields match say "Yes". If then they are asked, "and which is the redder", they respond quickly and accurately "the one on the left hand side". They appear not to notice the inconsistency in their responses. Despite these occasional problems, which are inherent in the test procedure, the results will be shown to be extremely valuable. (A discussion of reliability and validity is given on page 183).

The anomaloscope testing took place in a room with neutral painted walls. A 30 w. tungsten bulb was placed on the wall behind the patient's head, and the light scattered around the room by the back wall. The illumination at the front of the anomaloscope was about 11 lux thus approaching the photopic adaptational level. This illumination was sufficient to enable the experimenter to read the dials and to tabulate the data.

5. The Helmholtz Colour Mixer

(i) Description of the Apparatus

This apparatus made by Schmidt and Haensch (Berlin) consists of two mobile collimators which are symmetrically situated on each side of a prism of equilateral dispersion./



THE HELMHOLTZ COLOUR MIXER

Spektralfarbenmischapparat nach von Helmholtz Mod I.

Schmidt und Haensch
Berlin

Figure 64

dispersion. The prism is fixed, and the light from the collimators illuminates the heterolateral half of the photometric field which is observed by a fixed telescope. The angular position of each collimator is measured on a Vernier scale which is graduated to 30" of arc. Each collimator has a lamp house containing a 100 w. projection lamp, run from a stabilised voltage supply, and a circular exit aperture covered by opal glass. Light enters the collimator through a bilateral entrance slit whose opening is controlled by a graduated Vernier scale. There are two prisms on each collimator which can be varied to adjust the light falling on the fixed dispersion prism. One is a rotating polarising prism, after Glan-Thomson, the other is a birefringent Rochon prism which can be displaced along the collimator axis at measurable distances from the collimator entrance slit. Each collimator has an objective of 240 mm. The observation telescope consists of an objective whose focal distance is 240 mm; an eyepiece with a variable exit slit; and an accommodation magnifying glass.

The apparatus is shown in Fig.64 with legend in Table X. Light entering the collimator through the entrance slit is linearly polarised by the Glan-Thomson prism. On entering the birefringent prism it is split into two rays, an ordinary and extraordinary ray. The entrance slit of the collimator is situated in the focal plate of the collimator objective, and the exit slit/

T A B L E X

The Helmholtz Colour Mixer

Symbol	Part of Apparatus
L_1L_2	Source
l_1l_2	Condenser lens
N_1N_2	Nicol Prism
W_1W_2	Rochon Prism (split into two components)
S_1S_2	Collimator Slit
T_1T_2	Rach and Pinion Device for Rochon Prism
K_1K_2	Collimator
F_1F_2	Micrometer screw for collimator
P	Prism
O_1O_2	Collimator Lens
Sp_1Sp_2	Setting mirror
M_1	Ground glass
B	Variable slit
O_3	Telescope lens
R, L	Vernier scales
F	Telescope
T_3	Rach and Pinion Device for eye piece
A	Exit pupil
Al	Eyepiece
ND	Neutral Density Filter (variable)
M_2	Light Source for Flicker measurements
RSD_1	Rotating Sector Disc 1
RSD_2	Rotating Sector Disc 2
FS	Stray Light filter

slit of the observational telescope is situated in the focal plane of the telescope objective. Consequently, the entrance slit is reproduced in the plane of the exit slit by two images which are polarised at right angles. The distance between the images depends on the position of the birefringent prism along the collimator arm. If, for example, the extraordinary ray is not changed by longitudinal displacements of this prism, then the ordinary ray will be changed and will vary as a function of the displacement. The relationship between the luminances of the two images depends upon the angular position (φ) of the Glan-Thomson prism. This relationship is expressed by the law of Malus for rectilinear polarisation:-

$$\frac{\text{Luminance extraordinary ray } (L)}{\text{Luminance ordinary ray } (L')} = \frac{\sin^2 \varphi}{\cos \varphi}$$

It follows that single images are produced if the Glan-Thomson prism is set at either $\varphi = 0^\circ$, or $\varphi = 90^\circ$. The summation $(L + L')$ of the luminances is proportional to the widths of the entrance and exit slits.

The two images of the entrance slit in the plane of the telescope exit slit are two continuous spectra. By varying the entrance or the exit slit, it is possible to select a narrow waveband of the two spectra whose particular components depend upon the angular position of the collimator, and the longitudinal position of the birefringent prism along the collimator axis. The /

The luminances of the two spectral bands depends upon the position of the Glan-Thomson prism, and the sum of the luminances always depends on the widths of entrance and exit slits. The two spectral bands fall on the same retinal area and the mixture is additive.

Calibration curves for the instrument were obtained from the manufacturers for both right and left hand collimators. These enabled the collimators to be set for any wavelength and for any wavelength mixtures. As it was thought that the instrument calibration might have changed slightly over the period since purchase, the basic calibration curves were rechecked using the four principal wavelengths of a cadmium vapour lamp. The relationship between the wavelength and the collimator angle is given by the Hartmann equation:-

$$\lambda = \lambda o + \frac{c}{s - s_o}$$

where (λ), and (λo) are two wavelengths with corresponding angular settings (s), and (s_o) respectively. As the equation has three unknowns, three of the principal cadmium lines are sufficient to solve for the three unknowns λo, c and s_o. The three cadmium lines used were at 643.8 nm, 508.5 nm, 480.0 nm. The calibration of the instrument was performed by locating one of the lines in the telescope exit slit, and noting the collimator vernier scale reading at one edge of the line. The line spectrum was then moved across the slit, by adjustment/

adjustment of the collimator angle, until the other edge of the line appeared in the slit. The average value was used as the angular setting. This same technique was used to determine the width of the wavelength band presented to the eye at different settings of the entrance and exit slits. Although a narrow entrance slit is preferable, as it results in a closer approximation to monochromatic light, the lower limits of the slit width are set by diffraction patterns in the eyepiece, and low luminosities of the field of view. With a telescope slit of 0.8 mm. and collimator slit of 0.2 the wavelength band in the red at 644 nm. was 5 nm.

At the short wavelength spectral regions the collimator slit was adjusted to 1.0 mm. to increase luminosity of the photometric field. At this setting, the width of the wavelength band at 467.8 nm. (the shortest emission band for cadmium) was found to be 2.0 nm., and this width only increased to 2.3 nm. at 480 nm. A mercury lamp with an emission line at 423 nm. was used for shorter wavelengths. At this wavelength setting the width of the emission line was 1.2 nm., when the collimator slit width was 1.0 mm. It was considered justifiable, therefore, to use a collimator slit width of 0.2 for all wavelengths over 500 nm., and 1.0 for all wavelengths below 500 nm. The telescope exit slit was fixed at 0.8 mm. in all cases./

cases.

(ii) Instrument Modifications for Measurement of the Photopic Luminosity Function

Possible techniques for measuring the $V\lambda$ function were discussed on page 68. The most appropriate method for unsophisticated observers is generally considered to be the flicker fusion method, Le GRAND (1968). Firstly the task is relatively simple, secondly it is less time consuming than other methods, and thirdly, the individual variation in results is considerably less for this method than for alternative methods (e.g. that of the step-by-step). To utilise the Helmholtz colourimeter for this purpose, a third light source was added so as to illuminate the diffusing screen at M2 (see Fig. 64). This was a small microscope tungsten lamp of 12v. which illuminated the right hand observation field of the telescope. Two flicker sector discs were mounted on a spindle, and fixed so as to be 90° out of phase. One sector disc was mounted in the light beam illuminating M2, and the other sector disc was placed in the light beam from L1. When the spindle was rotated, the light entering the right hand observation field came alternatively from M2 and L1. Light L2 was used for photometric calibrations but not for flicker measurements, so that the left hand observational field was dark throughout all test measurements. A voltage doubling circuit was built to drive a DC motor connected to the/

the stabilised mains supply. A rheostat was included do that the speed of rotation of the flicker sector discs was variable. The same circuit also supplied the third fixed light source illuminating M2. The lamp L1 was connected to a regulac variable transformer with input from the stabilised mains supply so that its intensity could be altered in a continuous fashion. (This method is not normally employed for intensity variations as colour temperature also changes with voltage. However, it was specially chosen here because of properties which approximate to a full black body radiator, see below). To the normal regulac voltage control was fixed a gearing system with a ratio of 4:1. The reason for this was that with the standard regulac control, less than one full turn of the dial covered the voltage range from 0 - 230. It was difficult, therefore, to manipulate the control for very small voltage adjustments to the lamp, of the order of one or two volts. With the new system, over four full turns of the regulac control covered the same voltage range, resulting in a much more sensitive control of small voltage changes applied to lamp L1.

Finally, as the Helmholtz instrument is a single stage monochromator, stray light filters are necessary to cut down the scattered light from internal optical surfaces. Seven Kodak Wratten filters were selected for this purpose to cover the range of the visible spectrum./

spectrum. The filters were mounted on a circular disc so that they could be brought into the light beam from L1 for different wavelength settings of the collimator. The optical modifications are shown in Fig. 64.

(iii) Theory of the Method used in determining the Photopic Luminosity Function

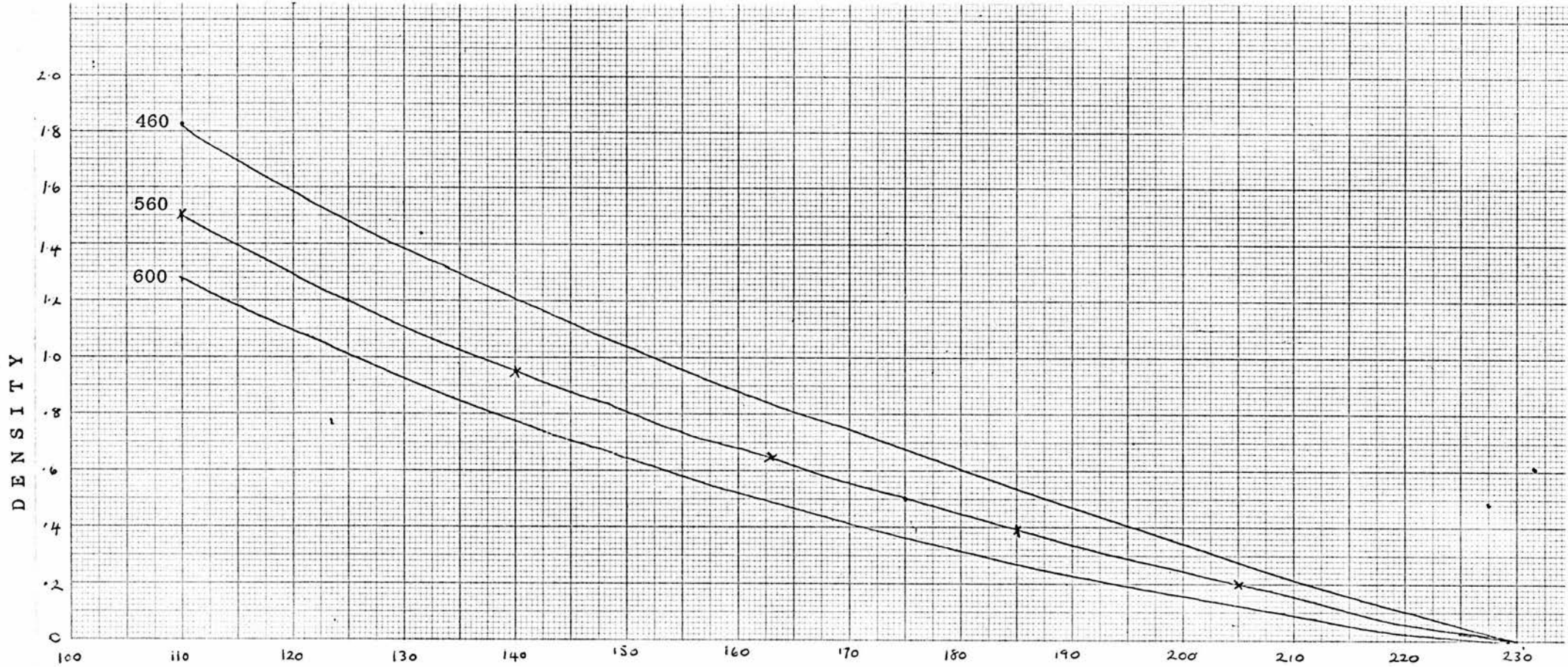
The method used for foveal luminosity measurements is based upon a principle used in the construction of a visual spectrophotometer (BUCKLEY and BROOKES, 1930). The photometric scale of the instrument is based upon intensity variation of lamp L1, obtained by voltage variations and a rotating sector disc of known transmission. The rotating sector disc was chosen because it acted as an ideal neutral non-selective filter. It was inserted in the beam from lamp L2, and rotated above the critical fusion frequency by a small electric motor, so that changes in voltage could be compared with optical density changes by a series of visual matches. Instead of using a number of fixed sector discs, each with a different transmission characteristic, a variable sector disc was constructed of two overlapping parts. Each part had equal areas which transmitted or blocked out the light. When rotating, the filter transmission depended on the ratio of open to closed areas. The two sections were mounted at the same point so that one sector disc could move over the other, giving transmission values from 50%/

50% (when the sectors completely overlapped), down to zero (when the sectors were adjacent and completely closed the circle). The sector discs were symmetrically constructed so that at any setting there were two open segments of angle θ°, and two closed segments of angle $(90 - \theta)^{\circ}$. The discs could be bolted firmly together for any angle of the open segment. Eight settings of this disc were chosen so producing eight neutral density filters. The optical density was calculated as follows. For each of the eight disc settings, the chord across both the open segments was measured and the average taken. The angles of the open segments were calculated and expressed as a percentage of the total disc, thus giving percentage transmissions for the sectors. The density of the sectors was calculated from the expression:density = log (1/t) where t is the percentage transmission of the sector. This method of calculation leads to highly accurate transmission values for the filters.

To calibrate the lamp L1, both collimators were adjusted to produce light of 560 nm. in the observation field when lamps L1 and L2 were switched on. The birefringent prism was set at zero and the Glan Thomson prism at 90° on both collimators. Under these conditions, monochromatic light enters both halves of the photometric field from the two lamps. The collimator slit was set at 0.2 mm. for lamp L1. The/

Figure 65

VOLTAGE/DENSITY CALIBRATION CURVE



The voltage control for lamp L1 was set at its maximum value of 230 volts, and the collimator slit for lamp L2 adjusted until a photometric match was obtained. The variable sector disc was set at one of its eight calibrated values and inserted in the light path from lamp L2. The voltage of lamp L2 was kept constant at 230 v. The sector disc was rotated above fusion frequency, and the voltage control of lamp L1 adjusted until the match was restored. The voltage reading was taken at photometric balance. The sector disc was then set to a new value and the procedure repeated until a set of voltage readings were obtained, each giving photometric balance with the eight densities of the sector disc.

The voltage density relationship is shown in Fig.65 The curve gives the intensity of radiation from lamp L1 at any voltage in terms of its intensity at the voltage when no sector is used. The calibration curve is different for different wavelengths; however when it is known at one wavelength, it is possible to deduce its value for other wavelengths. The radiation from a tungsten lamp matches for colour a black body radiator which defines the colour temperature of the tungsten lamp and is the true temperature of the black body. Thus the energy distribution in the visible spectrum for tungsten is almost identical to that of the full radiator operated at the colour temperature of tungsten./

tungsten.

At a temperature of (S), when tungsten has colour temperature (T), the distribution of energy in its visible spectrum is given by:-

$$E\lambda S d\lambda = kc_1 \lambda^{-5} e^{-c_2/\lambda T} d\lambda$$ where k is constant

For lamp L1, which is supplied by voltages V1, V2, with true temperatures S1, S2, and colour temperatures T1 and T2 respectively:-

$$E\lambda S_1 d\lambda = kc_1 \lambda^{-5} e^{-c_2/\lambda T_1} d\lambda$$

$$E\lambda S_2 d\lambda = kc_1 \lambda^{-5} e^{-c_2/\lambda T_2} d\lambda$$

Therefore $\frac{E\lambda S_2}{E\lambda S_1} = e^{-c_2\left(\frac{1}{T_2} - \frac{1}{T_1}\right)/\lambda}$ if k is independent of temperature

Taking logarithms:

$$\log.\left(\frac{E\lambda S_2}{E\lambda S_1}\right) = \frac{-C_2}{\lambda}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) = \log\left(\frac{E\lambda V_2}{E\lambda V_1}\right)$$

If the radiation at voltage V1 is taken as standard (i.e. the intensity of light at 230 v. becomes the standard intensity), the intensities at other voltages can be expressed as densities where density

$$D\lambda V_2 = -\log\left(\frac{E\lambda V_2}{E\lambda V_1}\right)$$

Hence $D\lambda V_2 = \frac{C_2}{\lambda}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$

Voltage							
70	0.380	0.352	0.329	0.302	0.295	0.276	0
71	0.367	0.356	0.319	0.294	0.280	0.265	0
72	0.354	0.335	0.307	0.287	0.270	0.256	0
73	0.341	0.314	0.295	0.276	0.260	0.247	0
74	0.328	0.302	0.283	0.265	0.250	0.238	0
75	0.315	0.295	0.271	0.251	0.240	0.229	0
76	0.303	0.275	0.259	0.240	0.235	0.216	0
77	0.301	0.262	0.246	0.234	0.220	0.207	0
78	0.299	0.253	0.233	0.229	0.214	0.198	0
79	0.297	0.242	0.220	0.215	0.200	0.189	0
80	0.295	0.231	0.207	0.200	0.195	0.180	0
81	0.272	0.219	0.194	0.197	0.184	0.169	0
82	0.250	0.207	0.185	0.185	0.176	0.160	0
83	0.228	0.195	0.176	0.170	0.169	0.151	0
84	0.206	0.183	0.167	0.160	0.152	0.142	0
85	0.184	0.171	0.158	0.147	0.145	0.133	0
86	0.170	0.158	0.146	0.139	0.136	0.121	0
87	0.157	0.146	0.135	0.128	0.125	0.112	0
88	0.144	0.134	0.124	0.117	0.115	0.103	0
89	0.131	0.122	0.113	0.106	0.100	0.094	0
90	0.118	0.110	0.102	0.095	0.091	0.085	0.
91	0.108	0.097	0.093	0.085	0.082	0.076	0.
92	0.097	0.088	0.083	0.077	0.074	0.068	0.
93	0.087	0.079	0.075	0.069	0.066	0.061	0.
94	0.076	0.070	0.067	0.061	0.058	0.055	0.
95	0.066	0.061	0.057	0.053	0.050	0.048	0.
96	0.052	0.048	0.045	0.042	0.040	0.038	0.
97	0.039	0.036	0.033	0.032	0.030	0.029	0.
98	0.026	0.024	0.022	0.021	0.020	0.019	0.
99	0.013	0.012	0.011	0.011	0.010	0.010	0.
100	0.000	0.000	0.000	0.000	0.000	0.000	0.

Voltage							
34	1.148	1.091	0.997	0.918	0.886	0.838	0.
35	1.125	1.071	0.976	0.901	0.864	0.821	0.
36	1.102	1.047	0.953	0.882	0.845	0.805	0.
37	1.079	1.024	0.934	0.864	0.823	0.783	0.
38	1.056	1.001	0.912	0.846	0.802	0.764	0.
39	1.033	0.978	0.891	0.828	0.797	0.756	0.
40	1.013	0.955	0.873	0.813	0.771	0.732	0.
41	0.998	0.935	0.852	0.801	0.753	0.717	0.
42	0.986	0.915	0.834	0.782	0.734	0.708	0.
43	0.974	0.895	0.816	0.763	0.725	0.683	0.
44	0.963	0.875	0.798	0.744	0.702	0.679	0.
45	0.956	0.855	0.783	0.725	0.695	0.655	0.
46	0.915	0.832	0.757	0.704	0.671	0.643	0.
47	0.884	0.805	0.734	0.683	0.658	0.622	0.
48	0.845	0.785	0.711	0.662	0.636	0.603	0.
49	0.813	0.755	0.688	0.641	0.611	0.585	0.
50	0.775	0.737	0.665	0.623	0.595	0.562	0.
51	0.857	0.713	0.654	0.602	0.574	0.548	0.
52	0.838	0.696	0.634	0.588	0.569	0.537	0.
53	0.719	0.679	0.618	0.574	0.557	0.524	0.
54	0.700	0.662	0.602	0.560	0.532	0.506	0.
55	0.681	0.645	0.586	0.546	0.528	0.494	0.
56	0.657	0.625	0.568	0.528	0.505	0.488	0.
57	0.637	0.605	0.556	0.512	0.484	0.469	0.
58	0.617	0.585	0.532	0.496	0.473	0.442	0.
59	0.597	0.565	0.514	0.485	0.455	0.435	0.
60	0.577	0.545	0.496	0.464	0.445	0.417	0.
61	0.557	0.529	0.472	0.450	0.418	0.403	0.
62	0.539	0.514	0.459	0.437	0.406	0.390	0.
63	0.521	0.499	0.446	0.420	0.394	0.377	0.
64	0.503	0.484	0.433	0.405	0.382	0.364	0.
65	0.485	0.469	0.425	0.395	0.375	0.351	0.
66	0.464	0.444	0.401	0.375	0.354	0.336	0.
67	0.443	0.421	0.383	0.356	0.338	0.321	0.
68	0.422	0.398	0.365	0.333	0.322	0.306	0.
69	0.401	0.375	0.347	0.325	0.306	0.291	0.

TABLE XI

VOLTAGE/DENSITY RELATIONSHIP FOR PHOTOPIC LUMINOSITY MEASUREMENTS

DENSITY D V = -Log (E V/E 100)

Voltage	Collimator angle	4.15	5.10	5.45	6.15	6.35	6.53	7.
	Wavelength	427	465	496	532	560	590	65
	560/	1.312	1.204	1.130	1.054	1.000	0.950	0.
0		2.265	2.061	1.964	1.820	1.731	1.647	1.
1		2.292	2.036	1.946	1.790	1.702	1.625	1.
2		2.319	2.012	1.932	1.761	1.674	1.598	1.
3		2.346	1.988	1.918	1.732	1.646	1.567	1.
4		2.373	1.964	1.904	1.704	1.618	1.540	1.
5		2.401	1.943	1.892	1.673	1.594	1.517	1.
6		2.827	1.902	1.851	1.628	1.561	1.485	1.
7		2.165	1.864	1.812	1.596	1.532	1.457	1.
8		2.048	1.826	1.773	1.564	1.497	1.425	1.
9		1.931	1.788	1.734	1.532	1.465	1.392	1.
10		1.814	1.752	1.695	1.500	1.432	1.364	1.
11		1.774	1.714	1.664	1.475	1.402	1.337	1.
12		1.734	1.678	1.633	1.440	1.370	1.305	1.
13		1.694	1.642	1.602	1.415	1.355	1.272	1.
14		1.654	1.606	1.571	1.385	1.327	1.253	1.
15		1.614	1.579	1.541	1.352	1.297	1.226	1.
16		1.598	1.532	1.496	1.316	1.265	1.204	1.
17		1.581	1.504	1.452	1.282	1.248	1.183	1.
18		1.564	1.486	1.408	1.248	1.217	1.154	1.
19		1.547	1.458	1.364	1.214	1.193	1.134	1.
20		1.532	1.433	1.325	1.181	1.177	1.115	1.
21		1.518	1.402	1.296	1.166	1.152	1.098	0.
22		1.488	1.374	1.272	1.152	1.131	1.074	0.
23		1.457	1.346	1.248	1.138	1.107	1.053	0.
24		1.429	1.318	1.224	1.124	1.086	1.034	0.
25		1.391	1.297	1.203	1.119	1.062	1.013	0.
26		1.363	1.267	1.174	1.086	1.035	0.986	0.
27		1.335	1.244	1.148	1.062	1.016	0.965	0.
28		1.304	1.221	1.122	1.038	0.993	0.942	0.
29		1.275	1.198	1.096	1.014	0.973	0.924	0.
30		1.244	1.175	1.073	0.992	0.956	0.904	0.
31		1.217	1.154	1.051	0.969	0.934	0.889	0.
32		1.194	1.133	1.035	0.952	0.912	0.863	0.
33		1.171	1.112	1.012	0.935	0.893	0.852	0.

For wavelength λ'

$$D\lambda' V_2 = \frac{C_2}{\lambda'}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

$$\frac{D\lambda V_2}{D\lambda' V_2} = \frac{\lambda'}{\lambda}$$

Hence $D\lambda' V_2 = \frac{\lambda}{\lambda'} D\lambda V_2$

Therefore once the voltage/density relationship is known at one wavelength λ, it can be found for any further wavelength λ'. As a check on the workings, experimental determinations of voltage against density were made at one wavelength longer than 560 nm., and one shorter than 560 nm. The predicted relationship was found to be in good agreement with the experimental points.

The calibration curves shown in Fig. 65 were based on $\lambda = 560$. Density values and different voltages are tabulated in Table XI. For all other selected wavelengths λ' each density value was multiplied by $560/\lambda'$ so completing the Table XI. (The wavelengths in Table XI represent those chosen for the photopic luminosity measurements).

For subsequent checks on the calibration curve, the variable sector was set at a known fixed value and the voltage read when a match was obtained. If this coincided with the calibration curve, the curve was correct. However, even if there was a slight variation,/

variation, the calibration curves for different wavelengths had the same basic shape, so that although the original curve was no longer correct for $\lambda = 560$, it would be correct for a new wavelength $\lambda 1$. If the density of the fixed sector is D, then for voltages V_1 and V_2 at which a photometric match is obtained with and without the sector in the beam from L_2, the densities on the calibration curve are d_1 and d_2. If the curve is still correct than $D_2 = (d_1 - d_2)$. If it is not correct $D = C\ (d_1 - d_2)$ where C is a constant. For wavelength $\lambda 1$ at which the calibration curve now applies.

$$D = (d_1 - d_2)\ \frac{\lambda 1}{560} = c\ (d_1 - d_2)$$

$$\text{Hence } \lambda 1 = 560\ \frac{D}{(d_1 - d_2)} \quad \text{or } \lambda 1 = 560\ C$$

If the calibration curve has changed and now refers to wavelength $\lambda 1$, a new set of values for $\lambda 1/\lambda'$ can be computed.

Checks were made on the curve at intervals of one month during the first twelve months the instrument was in operation and subsequently at less frequent intervals. Up to the present time it has not been necessary to modify Table XI as variations in the calibration curve were within the limits of visual matching errors.

The voltage system for the instrument was run from/

from a stabilised voltage supply of 230 volts. It is apparent from the calibration curve, that the change of density with voltage is greater at the lower voltages. This means that a small error in voltage will result in a greater error of density at the lower voltage regions of the scale. For this reason the intensity of the white comparison lamp M2 used in flicker measurements was adjusted, by means of Balzer neutral density filters, so that the null point for flicker was in the central voltage region and, if possible, away from the bottom end of the scale.

Finally the transmission characteristics of each stray light filter had to be measured at the wavelength at which they were used. To do this, both collimators were set at a selected wavelength, and lamps L1 and L2 were switched on so that a photometric match was obtained for some voltage V1. The appropriate stray light filter for that wavelength was placed in the light beam from L2, and a new voltage reading V2 corresponding to photometric balance obtained. If d_1 and d_2 are the densities from the calibration curve ($\lambda = 560$) at V1 and V2 respectively then the density of the filter D_F at wavelength λ_1 is given by:

$$D_F = (d_1 - d_2) \frac{560}{\lambda_1}$$

(The instrument was subsequently used in this way as a spectrophotometer, to measure the full transmission/

transmission characteristics of a set of filters).

Changes in slit width were also calibrated in situ. This was done by selecting the wavelength in both collimators at which the change was to be made. Lamps L1 and L2 were used to obtain a match with the slit at 0.2 mm. (the standard calibration width) and voltage V1. The slit was then opened to 1.0 mm., and the regulac adjusted to a new voltage V2 which restored a photometric match. The difference in intensity introduced by the change in slit width was given from the calibration curve. The density change was; $D = \frac{560}{\lambda_1} (d_1 - d_2)$ where d_1 is density at 560 nm. at voltage V1, and d_2 is density at 560 nm. at voltage V2. λ_1 is wavelength at which slit is changed.

Calibration of the neutral density filters placed before the white source at M2 was carried out by using lamps L1 and M2. This is normally given by the Balzer manufacturers to 5% accuracy in transmission. However, the visual measurement gives a more accurate assessment. To measure the amount of white light cut out by the filter, light M2 was alternated with wavelength 560 nm., until the null point of flicker was reached, by varying L1. The neutral density filter was then placed before M2 and the new voltage found for minimum flicker. The voltage difference gave the density of the filter from the calibration curve.

(iv) Test Procedure/

(iv) Test Procedure

The measurement of the photopic luminosity function consisted in selecting a wavelength from the left hand collimator and lamp L1, and flickering this alternately in the right hand observation field against the white light M2. The speed of the rotation of the flicker vanes was originally set fairly high, so that the null point was enlarged to form a band of zero flicker with a definite stationary point at the centre of the band. This was to ensure that the subject appreciated that a stationary point of minimum flicker did exist. The motor speed was then reduced to about 15 cycles/sec. which is just below the speed at which the flicker disappears entirely for a luminosity balance between monochromatic and white light. (The accuracy of measurement is greatest when some minimum flicker is preserved, and the variation in the degree of flicker between the null point and points adjacent to it is then most marked). Each selected wavelength was balanced against the fixed white light illuminating diffusing screen M2.

As the photopic luminosity function is a relative measurement of visual sensitivity at different spectral locations, the units of measurement are not important, and luminosities relative to the white source are sufficient. Despite the adjustments to the collimator slit to increase intensity in the blue regions of the/

the spectrum, the flicker measurements were found to be extremely difficult in this region. A series of neutral density filters were placed before the white source at M2 to facilitate measurement. However, the null point was still very difficult to find. The final solution was to abandom flicker measurements in the short wavelength regions and to use heterochromatic brightness matching instead. This was found to be much more satisfactory as a match existed at a clearly defined point, and in addition, the task was considerably easier than flicker photometry in these regions.

The test procedure in detail was as follows. The subject was dark adapted for ten minutes while the collimator entrance slit was set at 0.2 mm., and the Glan-Thomson prism at 90°. The birefringent prism was set at the zero point of the collimator axis and the telescope exit slit was set at 0.8 mm. A neutral density filter of 20% transmission was placed before the lamp M2 so that the null point was in the centre of the voltage range. The left hand collimator was set to 531 nm., the stray light filter rotated into place, and the flicker sector discs rotated.

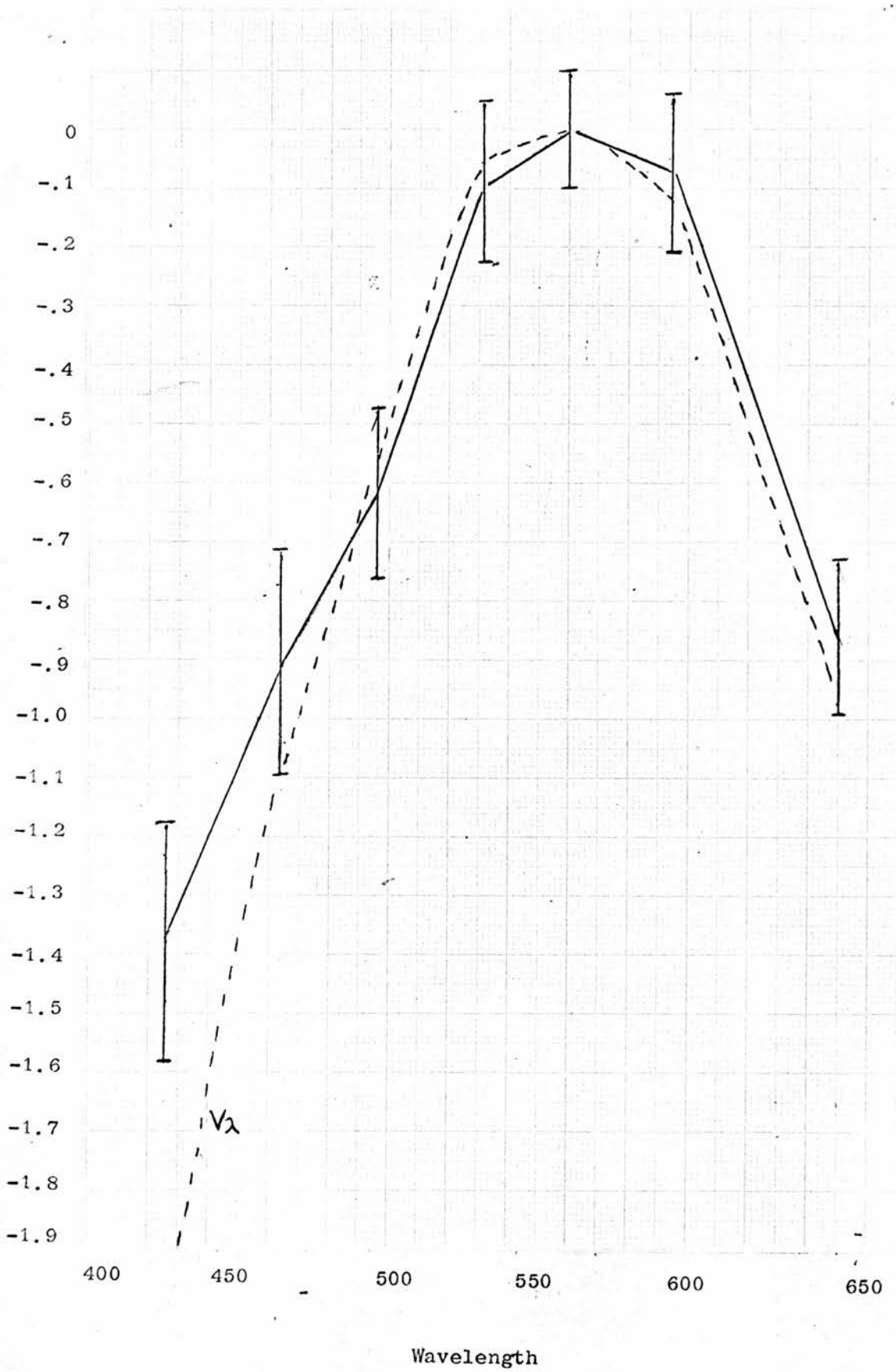
The null point was located approximately, by allowing the subject to adjust the voltage control. Subsequently, the subject was only allowed to observe the photometric field while the experimenter, using the method of limits, adjusted the voltage and approached/

approached the null point three times from lower and higher voltages. The average of the voltage control readings was taken. The collimator was then reset at 560 nm., 590 nm., 650 nm., and the procedure repeated at each setting. (Wavelength 531 nm. was always used to demonstrate the measurement to the subject, and as the first experimental setting, because a null point was very easily established at this wavelength). The collimator was then reset to 496 nm. and the collimator slit adjusted to 1.0 mm. The flicker measurement was then made. At the next setting of the collimator (i.e. at 464 nm.) the neutral density filter of 20% transmission which had up to this point been in front of light M2, was replaced by one of nominally 9.2% transmission. The final flicker measurement was then made. In order to measure the luminosity value for 426 nm. the heterochromatic matching procedure was used. For this, lamp M2 was switched off and lamp L2 switched on, so that the whole photometric field was in use. Both collimators were set at 464 nm. and a visual match established at a voltage reading towards the bottom end of the scale. The left hand collimator was then changed to 426 nm., and the voltage adjusted to re-establish a match. The voltage difference gave the luminosity difference between 464 and 426 nm.

The voltages were converted into densities using Table XI, which is based on the curve/

Figure 66

Mean and Standard Deviation of Photopic Luminosity Curve for age group 20-30 years (N = 21)



curve in Fig. 65. These densities were then adjusted by adding or subtracting, as appropriate, the various filter densities. Finally the densities at different wavelengths were related to that at 560 nm. by subtracting the density at 560 nm. from each of the other density values. Thus log $V\lambda$ at 560 nm. is always set equal to zero. The test was carried out on a $1\frac{1}{2}^{o}$ field of approximately 38 trolands luminance. The heterochromatic matches for the two short wavelengths were made at a luminance of 10 trolands.

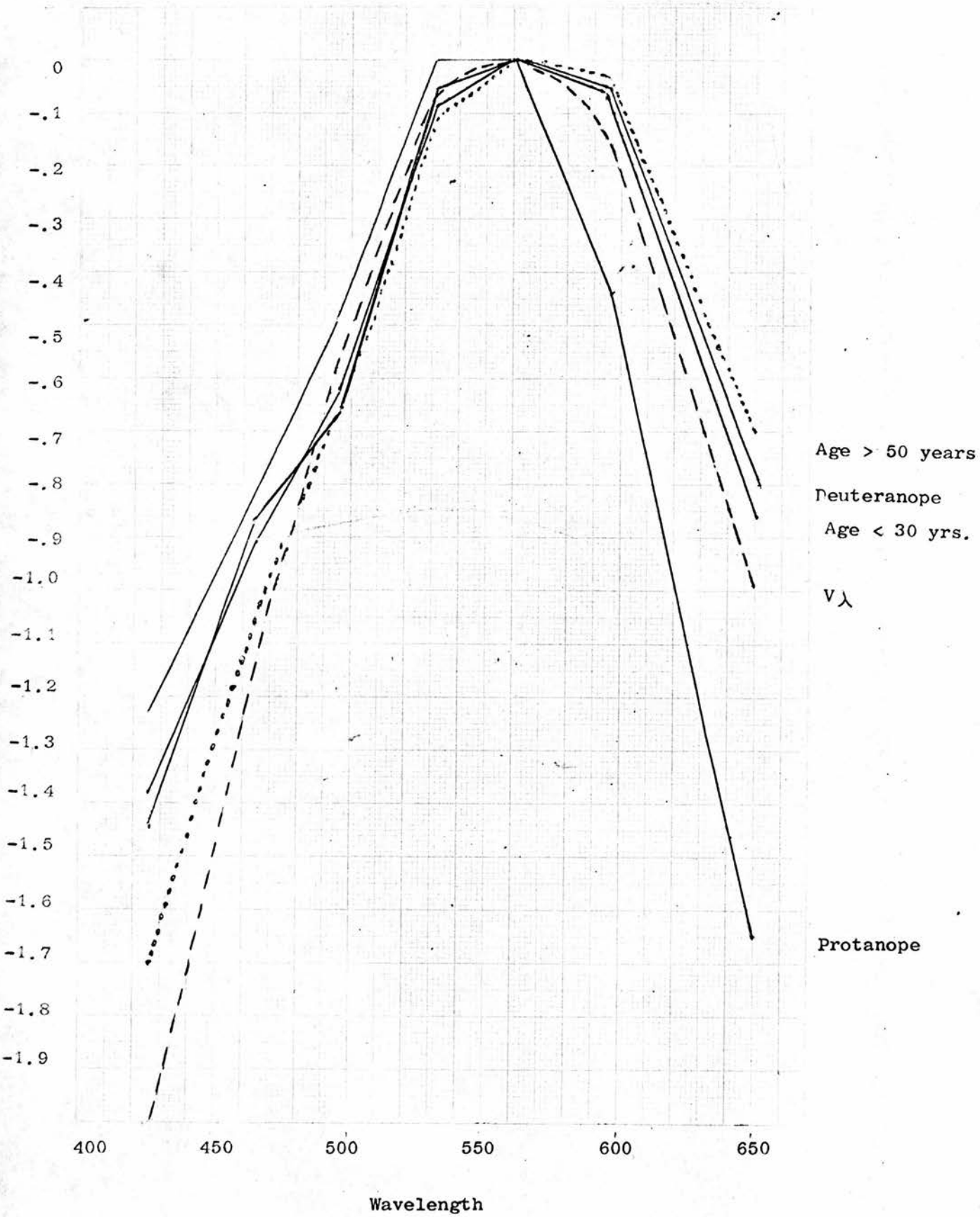
(v) Norms

Fig. 66 illustrates the individual variation in a group of 21 young individuals of age 20 - 30 years. The CIE photopic luminosity curve is also included for comparison. The values for each individual were first converted into density values before means and standard deviation were calculated. The population values are found to be normally distributed on a logarithmic scale. Furthermore, the logarithmic scale had additional validity for vision as approximately equal perceptual steps are found to be equal to logarithmic changes in the stimulus intensity (See Weber's Law page 239). This same principle will be used in the calculation of norms for perimetry and dark adaptation.

The noticeable feature in Fig.66 is the departure from the CIE $V\lambda$ curve at short wavelengths. This has/

Figure 67

The Photopic Luminosity Function for normals and colour defectives



has been reported by RUDDOCK (1965 and VERRIEST, (1970) and the CIE values have been criticised at short wavelengths (CIE proc. 1955). The standard deviation of the group results was smallest at the central region of the spectrum and largest at the extremities, particularly in the blue. The CIE value at 426 nm. was outside the limits of normality defined by this population. Changes in the luminosity function brought about by age or congenital colour defects are shown in Fig. 67. The deuteranopes curve, based upon seven observers, showed slight differences from the mean curve of the 20 to 30 year old group. However, the difference appeared to be an increased sensitivity to wavelengths, above 560 nm., or a slightly decreased sensitivity to wavelengths less than this. However, none of the differences were significant (Mann-Whitney U test). The protanope curve, based on four observers, did show the marked loss of sensitivity at the red end of the spectrum. The differences at 590 and 650 nm. were significant. The differences below 560 nm. indicated that the protanope had slightly higher sensitivity than normal at these wavelengths although the differences were not significant.

Finally age variations are added to Fig. 67. The main age effect is apparently to rotate the luminosity curve in an anti-clockwise direction about the 560 nm. point. Thus the relative sensitivity of blue was/

was reduced and the relative sensitivity to long wavelengths was increased. The loss of sensitivity in the blue region is to be expected from the increased absorption of short wavelengths by prereceptoral media as age increases. Mann-Whitney U tests of age differences, showed that a 30-50 year age group differed from the 20-30 year old group only at 427 nm. However, the over 50 age group showed significant differences at 427, 464 and at 650 nm. (The older group was more sensitive than the younger group at the 650 nm. point).

These results are in general agreement with those of VERRIEST (1971). The loss of protanopic sensitivity at the long wavelengths are well documented. (BOYNTON et al, 1959; WALD, 1966; MARRE, 1969; WATKINS, 1969) The slightly increased sensitivity in the short wavelengths are less so, although WILLMER (1949) and HSIA and GRAHAM (1957) have reported such an increase. The deuteranopic results indicating no significant difference from a normal luminosity curve have been reported by JUDD (1944) and WRIGHT (1946). On the other hand PITT (1944), WYSZECKI and STYLES, (1967), BOYNTON et al (1959), and HECHT and HSIA (1947), indicated losses in deuteranopic sensitivity at short wavelengths. WILLMER (1949) considered it necessary to divide the deuteranopic group into two types, one with normal luminosity and the other with a reduced luminosity curve. Verriest's extensive studies indicated several/

several significant differences between deuteranopes and normals, particularly an increase in sensitivity at long wavelengths in the deuteranope.

The age studies are in general agreement with RUDDOCK's (1965) findings showing that significant differences do appear with increased age, and those differences are most marked, as expected, in the short wavelength spectral region. The normal 20 - 30 year old's luminosity function is much higher in the short wavelength region. Age effects bring the curve closer to that of the CIE standard observer's in these regions but as Fig. 67 shows the agreement is not reached even in the oldest age group.

It was hoped that the development of the Helmholtz colourimeter towards measurement of the photopic luminosity function would help establish this function in different clinical groups. However, it was soon apparent that only those individuals with relatively good acuity could satisfactorily carry out the flicker measurement. Consequently, this has been used in the diabetic study, where most patients had 6/6 Snellen acuity, and in other isolated cases where acuity permitted. Any slight acuity loss increased the difficulty in the task, which was already relatively difficult for observers as they were required to view down a telescope. This emphasised once again the advantage of the Pickford Nicholson anomaloscope in which a telescopic/

telescopic system of viewing was not used.

(vi) Colour Matching Experiment

The Helmholtz instrument was used for colour matching in the diabetic population. For this, both collimators were used in conjunction with lamps L1 and L2. Lamp 2 was connected directly to a stabilised 230 v. mains supply, and the calibration voltage/density curve used in the last section was used to give intensity variations to lamp L1. The restriction in use because of the viewing situation, applies in this measurement as in the determination of the photopic luminosity curve. Two mixture ratios were tested, one at 590 nm. and the other at 495 nm. Light from lamp L2 was used to give the fixed wavelength in the left hand portion of the photometric field.

Mixture ratios were varied in the right hand half of the photometric field by adjusting the position of the birefringent prism along the collimator axis, and thereby changing the proportions of the extraordinary ray to the ordinary ray. For λ = 590 nm. the right hand collimator was set at 6° -45', and the Glan-Thomson prism at 90°. The left hand collimator was fixed at $7^{\circ}30'$ with the Glan-Thomson prism at 0°. A yellow Ilford stray light filter was placed before each collimator. The two variables necessary to obtain a match are the position of the birefringent prism (in mm.) and the intensity adjustments of lamp L1, made by/

TABLE XII

	Wavelength = 590	Wavelength = 496
Mid Matching Point	mean = 22.6	Mean = 57.4
Standard Deviation	= 0,26	= 1.0
Limits of Normality	22.09 - 23.11	55.3 - 59.5
Matching Range	0.57	2.1
Standard Deviation	0.31	1.3
Limits of Normality	1.19	4.8

NORMS FOR HELMHOLTZ COLOUR MATCHING AT 590 nm. and 496 nm.

by varying the voltage control. For λ = 496 nm. the right hand collimator was set at 5° 45', and the Glan-Thomson prism at 90°. The left hand collimator was again set at 7° 30', and the Glan-Thomson prism at 0°. The blue/green Ilford stray light filter was used before both collimators.

The measurement of colour vision is directly comparable to that of the anomaloscope, in which mixture ratios (mid-matching points) and matching ranges are measured. The difference between this test and the Pickford Nicholson anomaloscope, is that here monochromatic lights are used in both halves of the photometric field. The matches are consequently more metaneric than those made with broad band filters, and the test should on this basis, be more sensitive to individual variations in colour vision (see page 72).

In measuring the matching ranges, the method of limits was used to establish the approximate threshold positions. Following this the forced choice technique was used in which the subject was asked which of the two fields appeared of longer or shorter wavelength. The choice of 'no difference' was not permitted (See page 24 for a discussion of the method). The population best suited for this measurement was the diabetic one in which acuity losses were minimal. The wavelength choice for the matching stimuli was made as a result of an earlier experiment on diabetic colour vision which/

which is discussed on page 285. The norms for the measurement of colour discrimination at 590 and 496 nm. are given in Table XII. This normal population corresponded in age to the clinical group tested. Age changes are not included as no older clinical group was tested on this instrument.

b.) General Function

The tests described in the previous section have been confined to a viewing situation in which the central retinal area is utilised. Vision in an area with a retinal subtense of approximately 1.5^{o} about the fovea centralis was required for carrying out the majority of these tests. The purpose of the development of tests in this section is to investigate the visual function in other retinal areas, so that the additional information supplements that concerned with foveal vision. The tests used in this section fall into two general categories; firstly, that of perimetry, and secondly that of dark adaptation.

1. Perimetry

(i) Description of the Instrument

The instrument available for this measurement was the Goldmann Projection Perimeter manufactured by Haag Streit Liebefeld. This is a hemispherical projection perimeter with a semi-automatic recording device./

device. The instrument enables light thresholds to be measured at a series of fixed locations in the visual field (static perimetry) or enables a stimulus of constant size and brightness to be moved across the bowl until visible (kinetic perimetry). The stimulus is projected onto the inside of the hemisphere of radius 30 cms. By means of diaphragms and a set of neutral density filters, the size and brightness of the test object can be adjusted.

The light source (an Osram lamp 2700°K) which provides both the illumination of the target spot and the hemisphere adaptation light is situated in a lamp house inside the top of the bowl. By means of a voltage stabiliser, a rheostat, and a built in photometer, the brightness of a test spot and the background luminance in the bowl can be equated, so that the adaptational conditions are quantified. The photometer is calibrated in apostilbs (1 apostilb (asb) = 0.1 millilambert mL) and for recommended test conditions, the rheostat is adjusted until when the largest and brightest target falls on the photometer, the reading is equivalent to 1,000 asb. By placing the neutral density filters in the light path of the target spot, a match can be made visually between the spot brightness and the background luminance of the bowl. The brightness of the bowl is adjusted to that of the spot by a moveable shutter around the lamp house, which controls the amount of/

of light admitted into the bowl itself. Thus the brightness of the adaptational light can be set at a known value.

A pantograph arrangement enables the spot to be projected at any location on the inside surface of the hemisphere. The excentricity of a test object from the fixation point is immediately given on the recording system at the back of the instrument. The two sets of neutral density filters incorporated in the instrument have transmittance values of 1,00; 0.315; 0.10; 0.0315 which in standard settings provide luminances of 1,000; 315; 100; 31.5 asb., and 1.00; 0.80; 0.64; 0.50; 0.40 providing a further variation in the luminance of the test spot in steps of 0.1 log. unit. This provides luminance changes in steps of 0.1 log. units over a range of 2.0 log. units. In addition, a filter cap of density 2 log units may be placed over the projector to extend the luminances down to -1.5 log mL or 0.316 asb. The target size can be adjusted by placing a diaphragm in the light path consisting of apertures, whose sizes are 1/16, 1/4, 1, 4, 16, 64 mm^2. A flicker device is incorporated in the instrument which is operated manually by the examiner, so that the target can be presented and interupted at will.

A telescope at the back of the instrument enables the examiner to ensure that the subject is fixating correctly on the centre of the bowl while visual/

visual threshold measurements are taken. Cross wires on this telescope with millimetre gradations are used, firstly to centre the subjects eye with respect to the fixation spot, and secondly to measure the pupil diameter. Two milled knobs enable the examiner to adjust the position of the headrest, so that the subject's eye can be recentred on the crosswires when required. The distance of the subject's eye from the crosswires is approximately 30 cms. A moveable lens holder attached to the bottom of the bowl is used when refraction for this distance is necessary. Finally, a second fixation device projecting either a single spot, or four dots in a diamond configuration, is used for parafoveal and foveal measurements respectively.

(ii) Introduction to Perimetry

The method used in this section for an analysis of retinal threshold gradients was static perimetry. Its advantages as a precise estimate of visual function have been stressed by several authors and it is best seen as complementing the information obtained by the more common technique of kinetic measurement in visual field examinations (HARMS and AULHORN, 1959; HARMS, 1969; GOUGNARD, 1963; FANKHAUSER and SCHMIDT, 1958, 1960; SLOAN, 1961; SLOAN and BROWN, 1962; VERRIEST and ISRAEL, 1964; WEEKERS and LAVERGNE, 1958; AULHORN, 1962; ASPINALL, 1968).

In the detection of early functional losses/

losses WEEKERS and LAVERGNE (1958) suggested the use of static perimetry in preference to kinetic. For AULHORN (1962) the best method of perimetric investigation "returns exactly and completely the dispersion of function in the retina as it actually is. Only such a true to life field of vision has real value for diagnosis and therapy. Inexact fields of vision express little or can often mislead." (in translation). Cases of field disturbance which cannot fully be measured by kinetic perimetry are listed as:-

a.) flat gradients across the retina

b.) relative central scotoma

c.) paracentral scotoma

d.) the depth of a scotoma

e.) a series of narrow thin scotomas where there exist together side by side areas of normal function and strongly reduced function.

These instances illustrate the benefit of testing at any selected retinal location and assessing accurately the function as it exists at the selected point.

It should be mentioned that the results from kinetic and static perimetry are not directly comparable because of the method of measurement. In kinetic perimetry, the threshold point at which the target becomes visible depends to some extent upon the receptors adjacent to this point summating their information as the stimulus passes across them. In static perimetry the stimulated/

stimulated retinal area is fixed for each threshold determination. As the static measurement is time consuming, only a relatively small amount of information can be collected. How reliable or detailed any measurement is depends upon the interests of the tester, and a practical compromise must be reached. For example, if the measurement is restricted to a horizontal meridian through the fovea and optic disc, the locations at which measurements are taken may be spaced at 10° intervals in the periphery, and the threshold measurements repeated three times at each point (see page 334 for a description of the experimental error inherent in the measurement). On the other hand it may be considered preferable to test only once at each retinal location and so increase the number of positions in the meridian at which measurements are taken. Again a specific scotoma can be profiled in detail in preference to testing at other retinal locations. Consequently, it is necessary to use static perimetry in a flexible way depending on the population under investigation. The most frequent way of assessing general visual function under any of the adaptational conditions (see below) has been to measure differential thresholds across the horizontal meridian. (This applies to all patients with the exception of those in the Glaucoma study for which special test conditions were designed). In addition other regions of the visual/

visual field have been measured where clinical evidence suggested that the region was one of special interest.

(iii) Variables in Static Perimetry

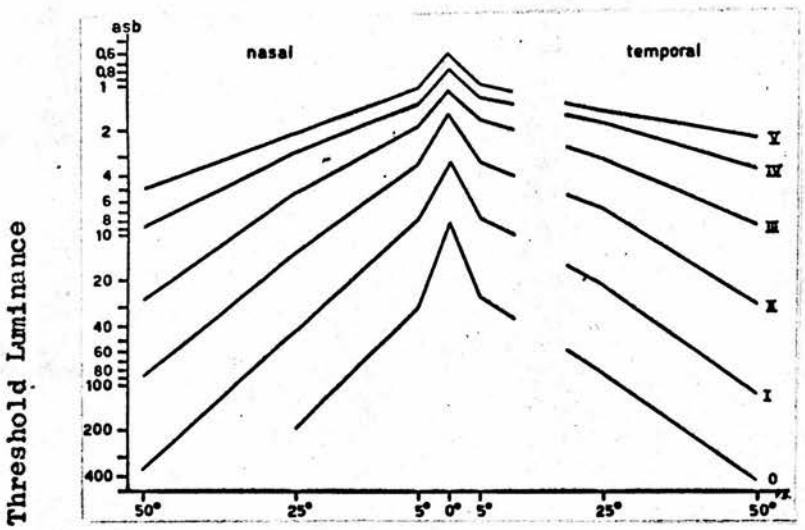
In the present study there are three adaptational conditions under which differential thresholds were measured. Firstly, the standard Goldmann conditions were used with norms established by ASPINALL (1968). Secondly, two further adaptational conditions were chosen, one of very high intensity to facilitate the photopic response, from peripheral retinal regions, and the other with zero background adaptation to facilitate the scotopic response of the peripheral retina. The three different conditions of testing have been used for different populations under study. The reasons for their choice will be described in the appropriate section in which they are used. Apart from the adaptation conditions, the second variable of great importance in static perimetry is the size of the test target.

The relationship between the size and the luminance of the test spot at threshold is complex. It has generally been accepted that some form of inverse relationship between area and intensity holds. Several authors have attempted to formulate simple laws governing this relationship (RICCO, 1877; PIPER, 1903; GRAHAM et al, 1939; WALD, 1938; SPERLING and LEE, 1957). However, it does appear as AULHORN (1964) points out that "although the threshold light intensity values of light/

light sense agree with the values required according to Piper or Ricco within a certain range of test sizes, no fundamental significance can be ascribed to the two laws since the light sense found dependent on the size of the test object can never be represented by a straight line, while the values required according to Ricco or Piper for light sense always forms straight lines within the same system of co-ordinates." Aulhorn furthermore suggests that the processes leading to the perception of light are of such a complex nature that the search for a simple law can never be successful:- "Light sense represents a physiological parameter which is influenced by every change in the stimulus situation."

Although these investigations might appear of purely theoretical interest, DUBOIS-POULSEN (1952) showed that the relationship between area and intensity for two different sized test objects was affected, and was abnormally high, in certain forms of ocular disease. For example, suppose that two test objects, one small and bright, the other larger and dimmer, are visible at the same retinal location in the normal eye. Then in certain clinical conditions, the visibility of the larger target is greater than that of the smaller, so that in kinetic perimetry, although the two targets have originally equivalent isopters, there is now a wider field to the larger and dimmer target than to the smaller and brighter one. DUBOIS-POULSEN called/

RETINAL THRESHOLD GRADIENT



Threshold Luminance

Excentricity

Background: 40 asb.

Figure 68

called such cases a disorder of "spatial summation". A reduction in target size would appear to be of more significance in reducing the size of the field than a reduction in luminosity.

The shape of the curve obtained with different sized test objects is shown in Fig. 68 after FANKHAUSER and SCHMIDT (1958). The important change is a flattening of the profile as the size of target is increased. In other words, the increase in sensitivity occurring with increase in target size is much greater in the peripheral retina than in the fovea.

This is equivalent to saying that spatial summation is greater in the peripheral retina.

The background adaptational level also affects summation. The authors found that summation was greater as the adaptational level was decreased, and that the summation increased by similar increments in the central and peripheral retina. The background illumination also influenced the basic shape of the retinal threshold gradient. Reducing the adaptational level flattened the curve, similar to the effect of increasing target size under standard illumination conditions. This flattening was intensified for large target sizes to such an extent that a relative central scotoma was produced with the largest targets at 0.04 asb. illumination. For the small targets, the maximum sensitivity was still/

still at the fovea.

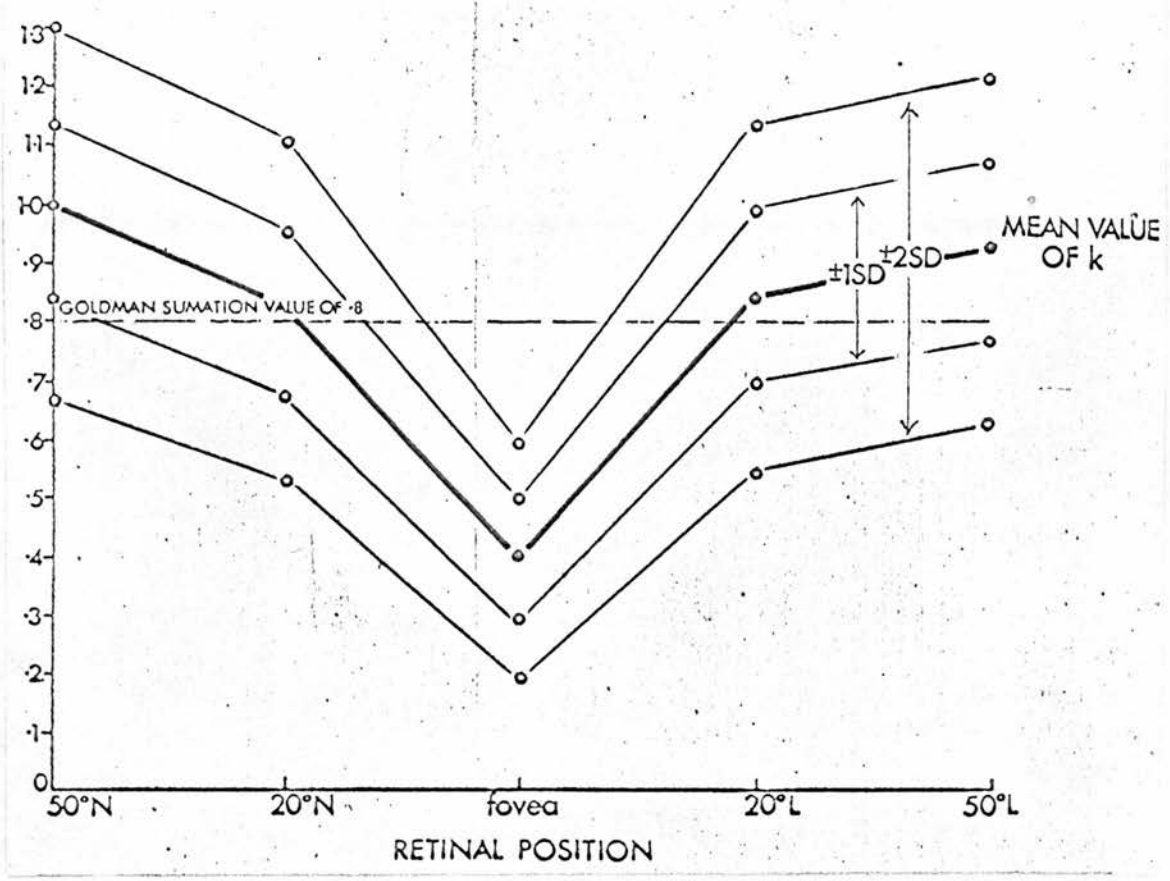
In an examination of the variability of results in a normal population, the greatest scatter was found at low background illumination levels, but there were no significant differences between the scatter of results for a given target size at different background illuminances. Similarily, correlation coefficients between scatter, size of test objects, and excentricity within individual adaptation groups were not significant although the scatter did increase in some cases in the periphery. In measurements of spatial summation the authors considered that only large deviations in the summation coefficient (greater than 50%) could be considered pathological.

If the coefficient of spatial summation is to be a useful clinical index of the normality of visual function, then limits to its range are important. In an attempt to assess this variation, ASPINALL (1968) measured the coefficient between different age groups, and between different targets. The coefficient of spatial summation (k) is defined by the equation:-

$$\log L + k \log A = \text{constant}$$

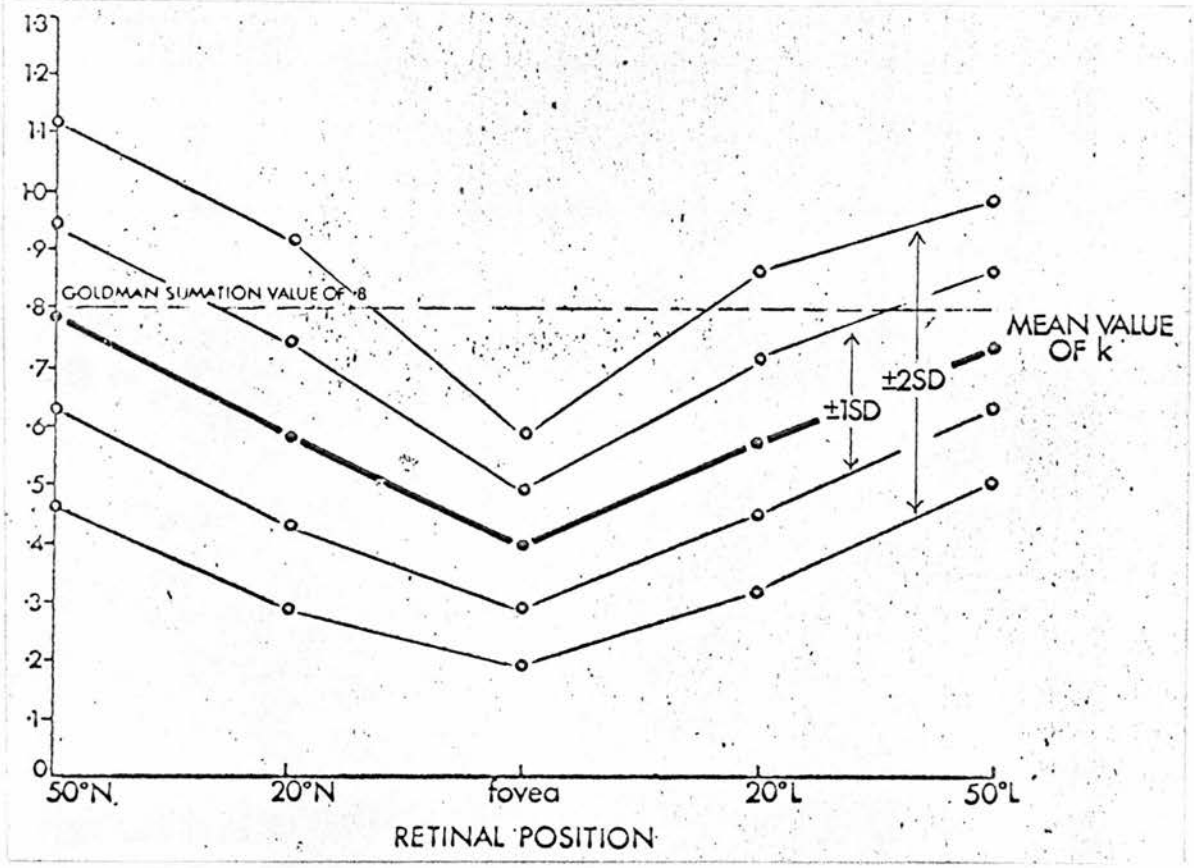
Where L is the luminosity and A the area of the target at threshold.

Consequently, for two targets in which the threshold conditions at the same retinal point are A_1L_1, and A_2L_2./



VARIATIONS IN VALUES OF k FOR TEST OBJECTS $\frac{1}{4}mm^2$ AND $1mm^2$

VALUES OF SUMATION COEFFICIENT k



gure 69

VARIATIONS IN VALUES OF k FOR TEST OBJECTS $1mm^2$ AND $4mm^2$

and A_2L_2.

$$k = \frac{\left(\text{Log } L_1 - \text{Log } L_2\right)}{\left(\text{Log } A_1 - \text{Log } A_2\right)}$$

Three Goldmann targets were used, $\frac{1}{4}$ mm.^{2}; 1 mm.^{2}; and 4 mm.^{2}. The variations in the value of k are shown in Fig. 69 for a population including different age groups. Although the theoretical limits to k are zero (no summation) and one (complete summation) the experimental results show values greater than the theoretical limit, particularly in the retinal periphery. Three striking features of these figures are firstly, the increase in the value of k from fovea to periphery; secondly, the greater value of k between the two small targets at all retinal locations; and thirdly, the wide variation in the value of k itself. Standard deviations for different sized test objects are shown in Table XIII indicating a similar spread of results for different target sizes.

The age effect on the summation coefficient is shown in Table XIVand Fig. 70,71. With increasing age, the threshold value for each of the three test objects is lowered. In the fovea and at 20° excentricity, this drop in sensitivity for the $\frac{1}{4}$ mm.^{2} target is approximately the same as it is for the other two target sizes. In other words the three different target sizes are affected roughly to the same extent with increasing/

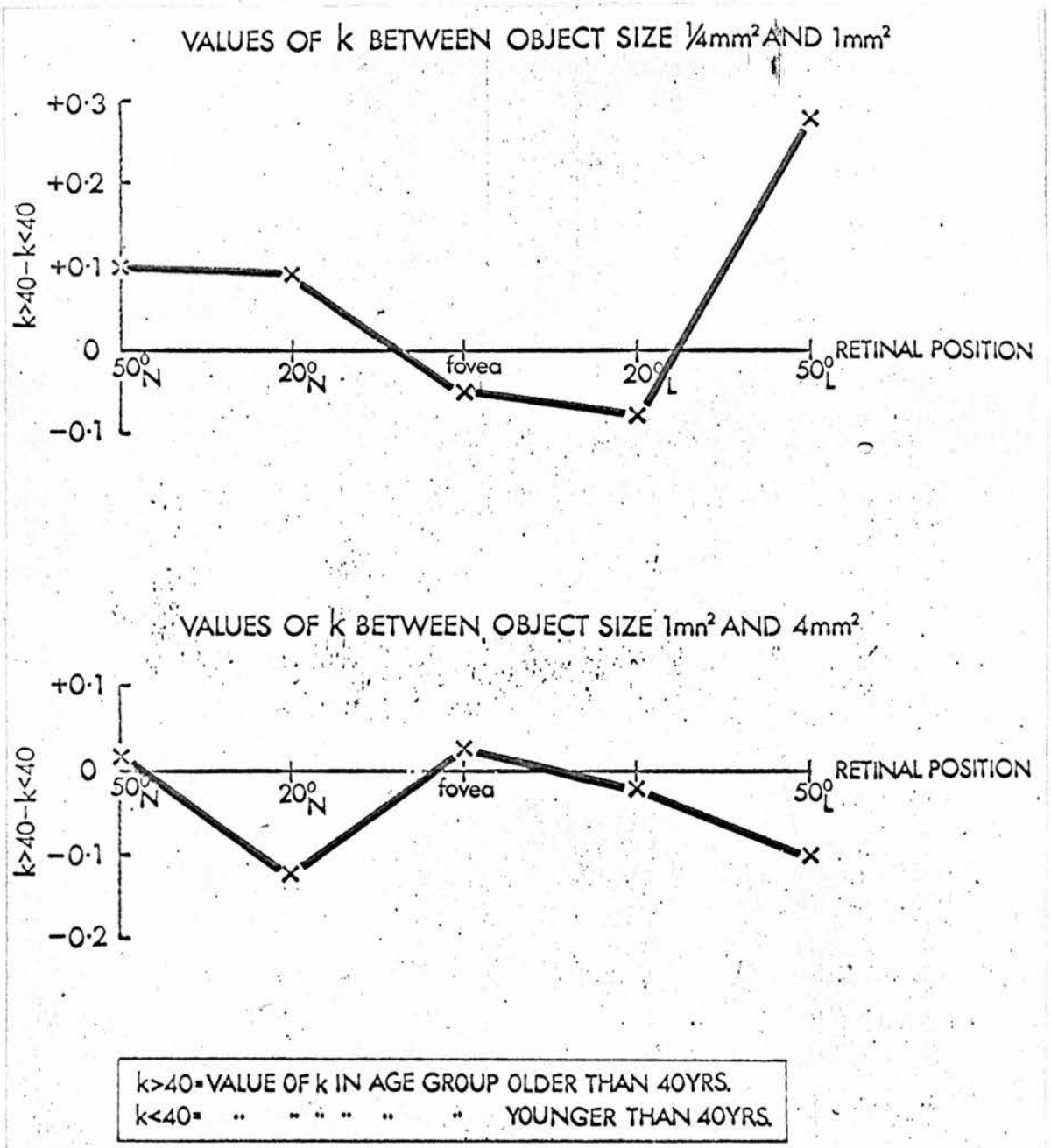
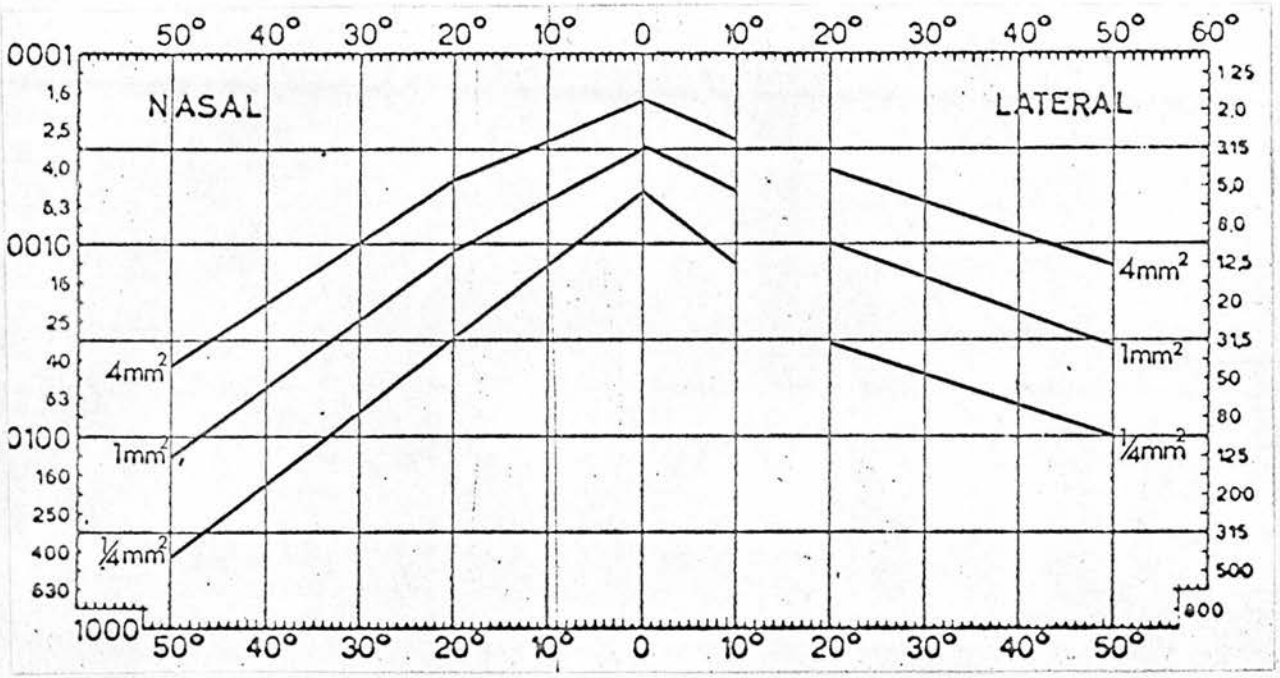

VALUES OF k BETWEEN OBJECT SIZE ¼mm² AND 1mm²
+0·3
+0·2
+0·1
0
−0·1
k>40−k<40
50° N
20° N
fovea
20° L
50° L
RETINAL POSITION
VALUES OF k BETWEEN OBJECT SIZE 1mn² AND 4mm²
+0·1
0
−0·1
−0·2
k>40−k<40
50° N
20° N
fovea
50° L
RETINAL POSITION
k>40 = VALUE OF k IN AGE GROUP OLDER THAN 40YRS.
k<40 = " " " " " " YOUNGER THAN 40YRS.

Figure 70

AGE GROUP < 40

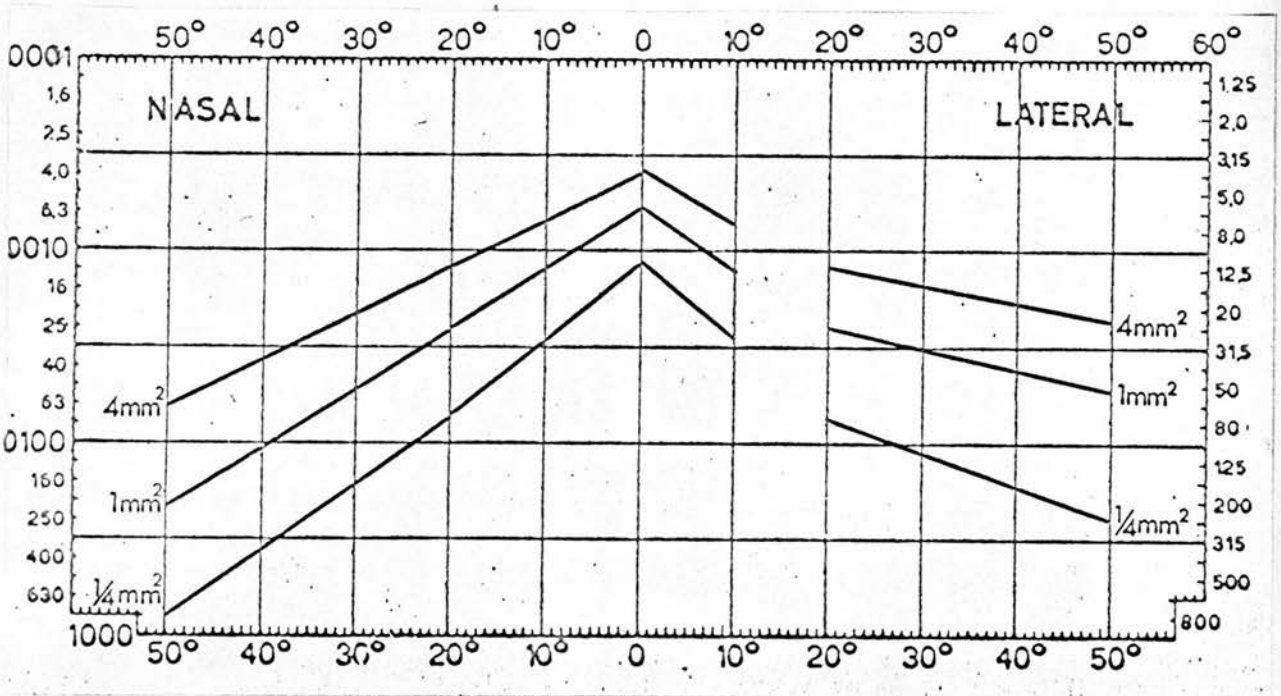
Near Vision 9.1 Pupil Diameter 4.8 N=13 Age: 26



TEST TARGETS ¼, 1 and 4mm²

AGE GROUP > 40

Near Vision 8.5 Pupil Diameter 4 N=11 Age: 50



TEST TARGETS ¼, 1 and 4mm²

Figure 71

increasing age. However, at the periphery the decrease in sensitivity for the 1 mm.^{2} and 4 mm.^{2} targets is less than the decrease in sensitivity for the smallest target. That is, age has a greater effect on the $\frac{1}{4}$ mm.^{2} target in the periphery than it has on the two larger targets. Because of this, the increase in the difference threshold between targets $\frac{1}{4}$ mm.^{2} and 1 mm.^{2} in the older age group, results in a higher summation value for the older group than for the younger one. This trend of an increase in the value of k with increased age, is in the same direction as the findings of DUBOIS-POULSEN (1952) for pathological cases. It is not that the retinal sensitivity to the stimulus has increased, but rather that the small test object has suffered greater losses with age than those occurring with larger test objects. Fig.70 illustrates that the value of k changes slightly with age, but in the majority of situations this change is small, and well within the limits of k already given for this population. The one exception, where a trend does appear to exist is at 50° for $k_{\frac{1}{4},1}$ where the value increases both in the nasal and temporal fields.

These findings suggest the following general points. The variability of the value of k is considerable. Goldmann's constant summation value, assumed in the construction of the instrument to be equal to 0.8 (dotted line Fig. 69), is within normal limits at the/

TABLE XIII

Area of test object	Retinal Location				
	50°N	20°N	Fovea	20°L	50°L
¼mm.²	0.23	0.22	0.18	0.25	0.20
1mm.²	0.24	0.21	0.19	0.23	0.20
4mm.²	0.24	0.22	0.16	0.26	0.22

STANDARD DEVIATIONS FOR DIFFERENT TEST SIZES

TABLE XIV

Age	Object sizes	Retinal Position				
		50°N	20°N	Fovea	20°L	50°L
Age group <40	¼mm.² - 1mm.²	0.90	0.75	0.42	0.92	0.80
	1mm.² - 4mm.²	0.80	0.67	0.40	0.62	0.78
Age group >40	¼mm.² - 1mm.²	1.00	0.84	0.37	0.84	1.08
	1mm.² - 4mm.²	0.81	0.53	0.42	0.58	0.67

VALUES OF SUMATION COEFFICIENT (k) FOR TWO AGE GROUPS

the periphery but outside these limits at the fovea. Correlations between the value of the summation coefficient and the absolute threshold values of the two targets used in its calculation, show that it is the smaller target which contributes most to the variance of k. This is true for intra retinal variation and also for age variations. If the small target is reflecting variations in the value of k, then from the practical viewpoint it might be sufficient to test fields to the small target alone.

The value of k is computed from two experimental determination of $\Delta L/L$, each with its inherent experimental error. GREVE (1972) reports that in static perimetry the threshold range from zero to 100% detection is 0.4 log units in a trained observer (see, also page 334). This is a considerable intra observer variation of the same order as individual variations with age (See Fig. 77). As two estimates of $\Delta L/L$ are required for the determination of the value of k, each with a variability of 0.4 log units, we can see that the experimental error in the computation of k becomes very large. This error will form part of the experimentally determined normal variation in k, and may account for the experimental values lying outside the theoretical limits, i.e. greater than $k = 1$. (The errors will increase when untrained observers are tested). Because of this variability in its computation, it would seem/

seem easier to pass from a known pathological abnormality to a corroboration of this in the respective k coefficient, than to make a diagnosis in pathological terms from a given k coefficient. Yet in spite of these problems some authors have suggested positive relationships between summation and pathology.

For instance SLOAN and BROWN (1962) suggest that an abnormality in spatial summation occurs with impairment in the cone receptor mechanism. (Normal values were found in congenital night blindness and pigmentary degenerations of the retina). The authors recommend using small test objects, as early field defects should be more easily detected by a decrease in the size rather than by a decrease in luminance of the target. (It was almost always the small test objects which showed the greatest increase in threshold). Therefore, the evidence would appear to be overwhelming in favour of the use of small targets in static perimetry.

The limits to target size are set by the luminance values of the target which enable small peripheral objects to be seen. The most appropriate size, therefore, for present purposes was the $\frac{1}{4}$ mm.^{2}, which gave on scale threshold values at 50° excentricity in old subjects. This was the size selected for most tests. The effect of age on the retinal threshold gradient has been discussed briefly on page 131. This variable, together with the pupil diameter and the effects of/

AGE GROUP I

Near Vision 9.2 Pupil Diameter 5.24 N=21 Age: 25

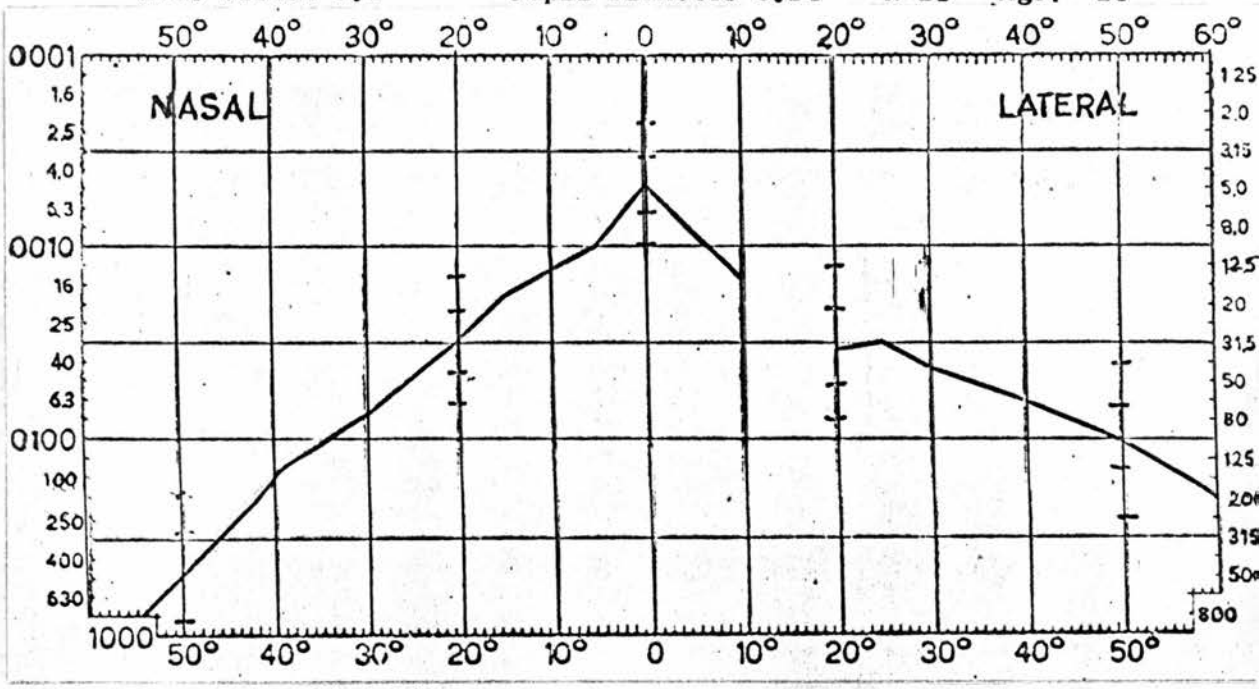


Figure 72

AGE GROUP II

Near Vision 9.2 Pupil Diameter 5 N=27 Age: 26-35

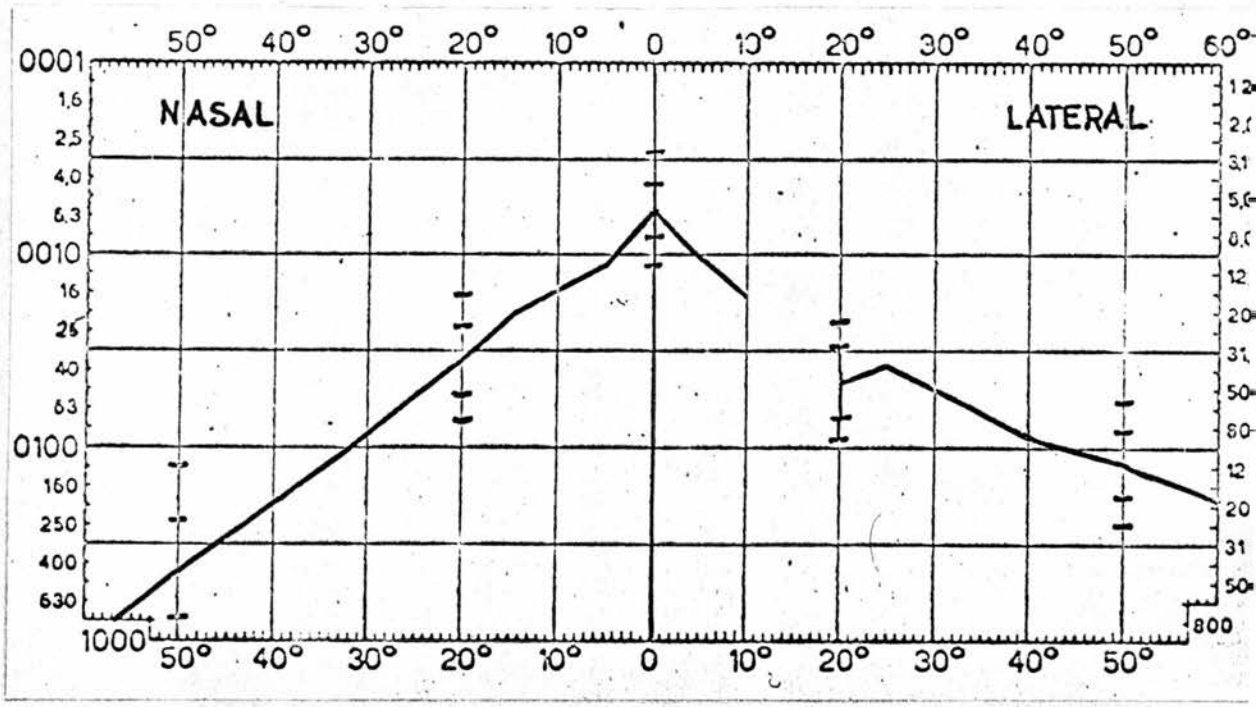


Figure 73 MEANS FOR AGE GROUPS AND STANDARD DEVIATIONS

AGE GROUP III

Near Vision 8.6 Pupil Diameter 4.4 N=25 Age: 36-45

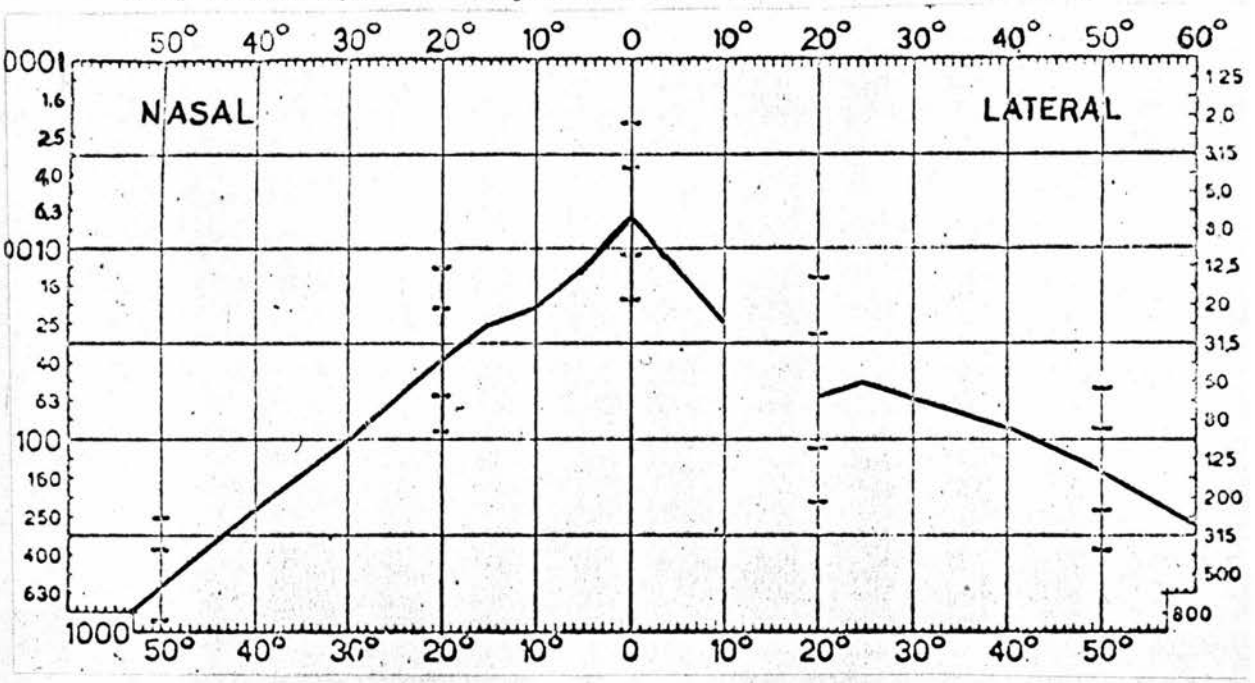


Figure 74

AGE GROUP IV

Near Vision 8 Pupil Diameter 3.83 N=20 Age: 46-55

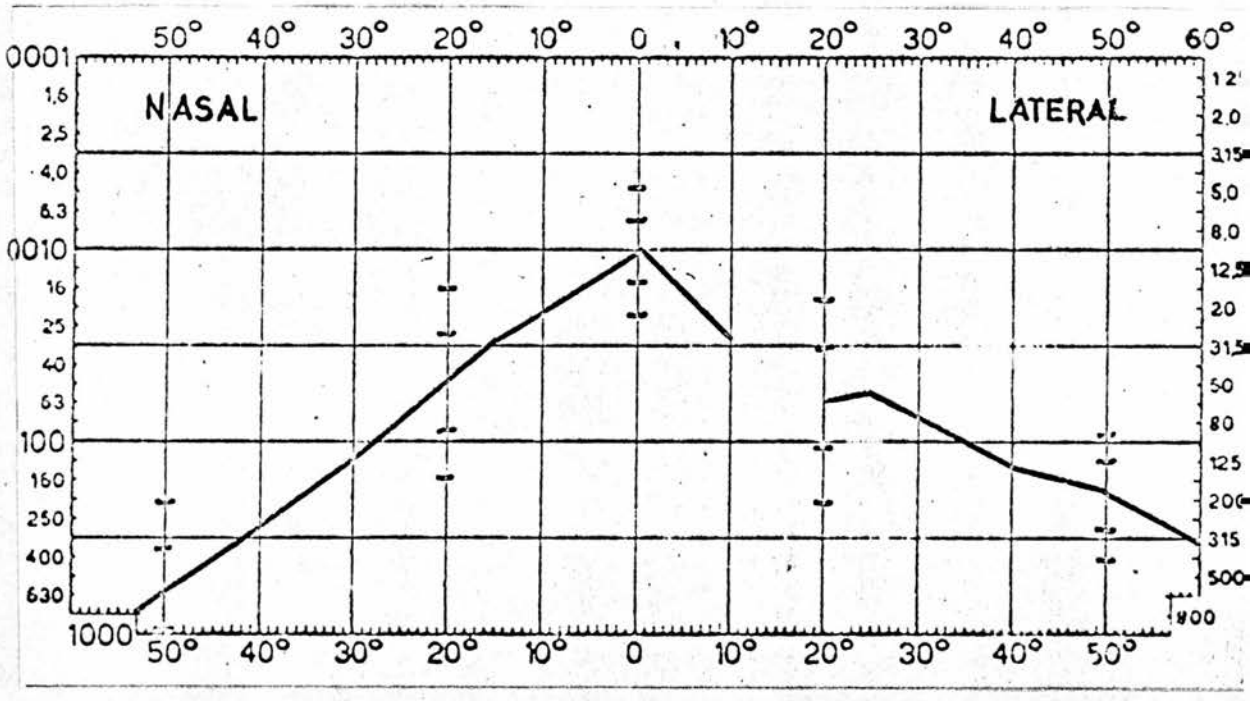


Figure 75 MEANS FOR AGE GROUPS AND STANDARD DEVIATIONS

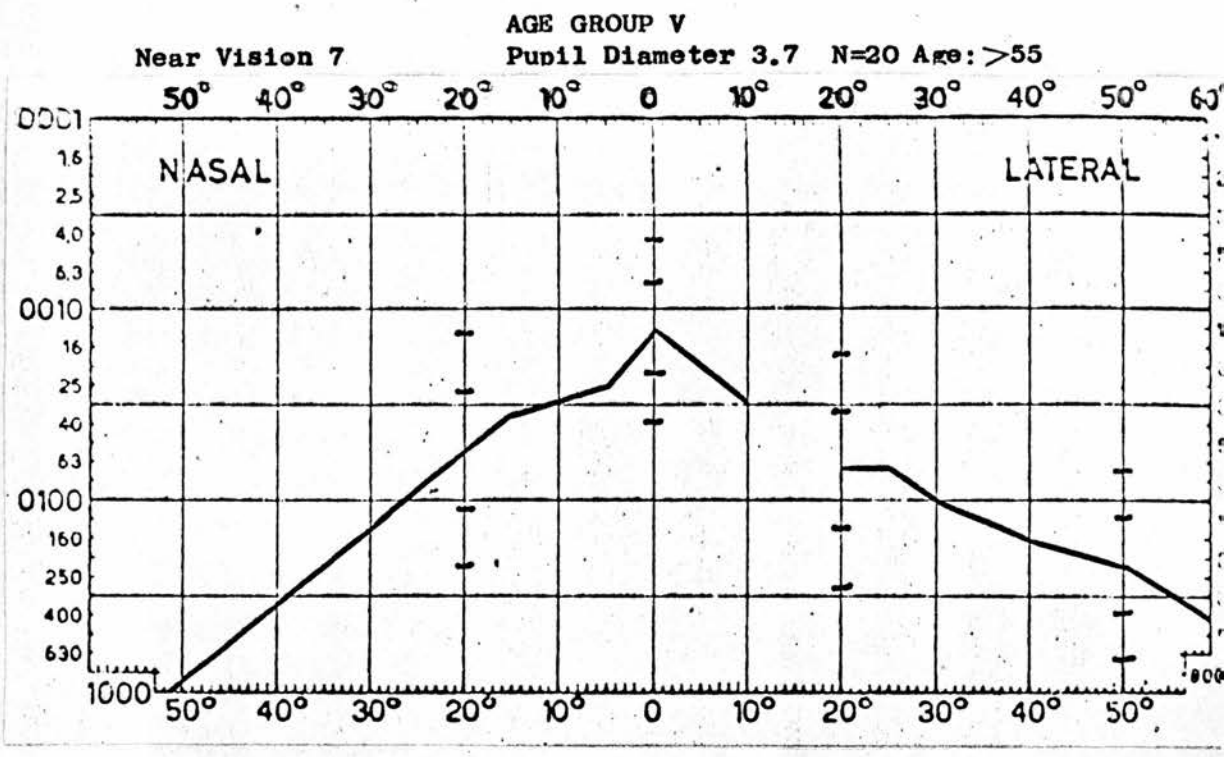


Figure 76 MEANS FOR AGE GROUPS AND STANDARD DEVIATIONS

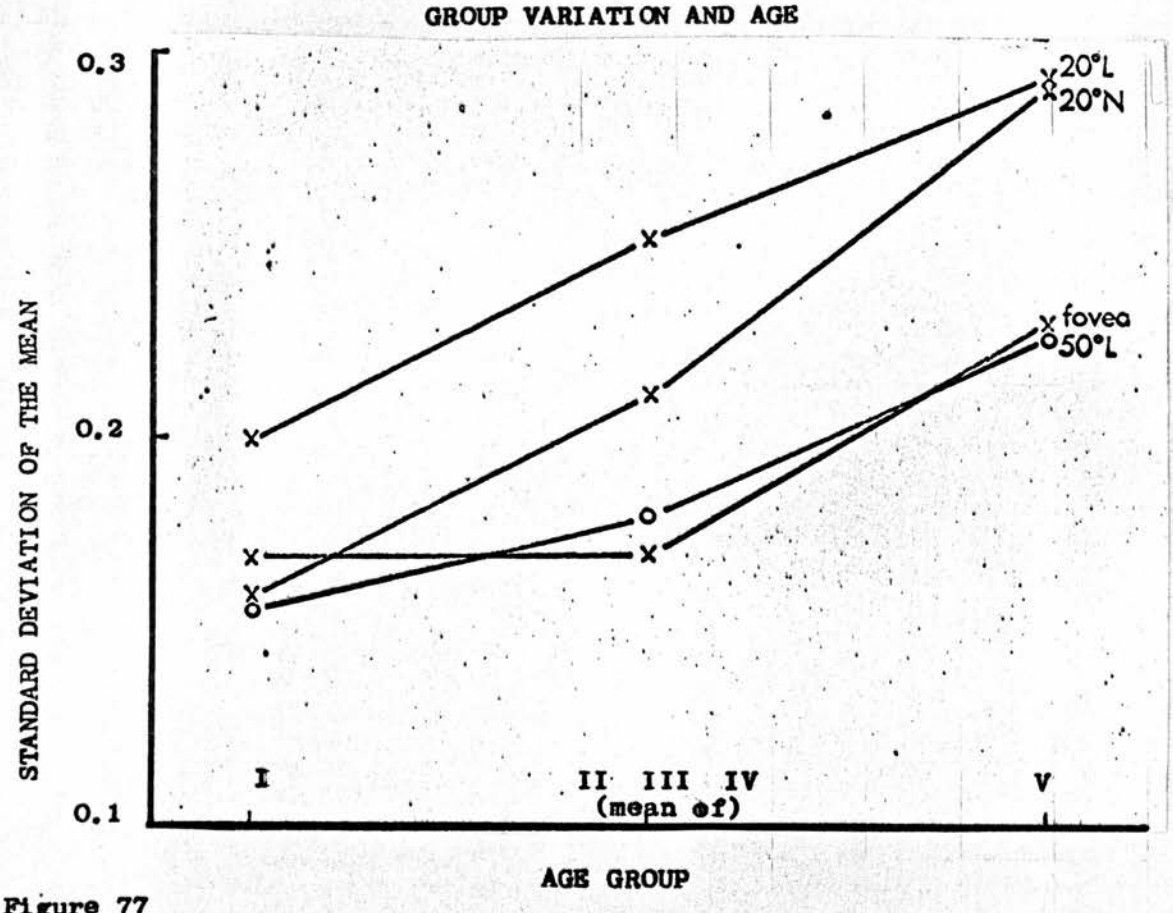


Figure 77

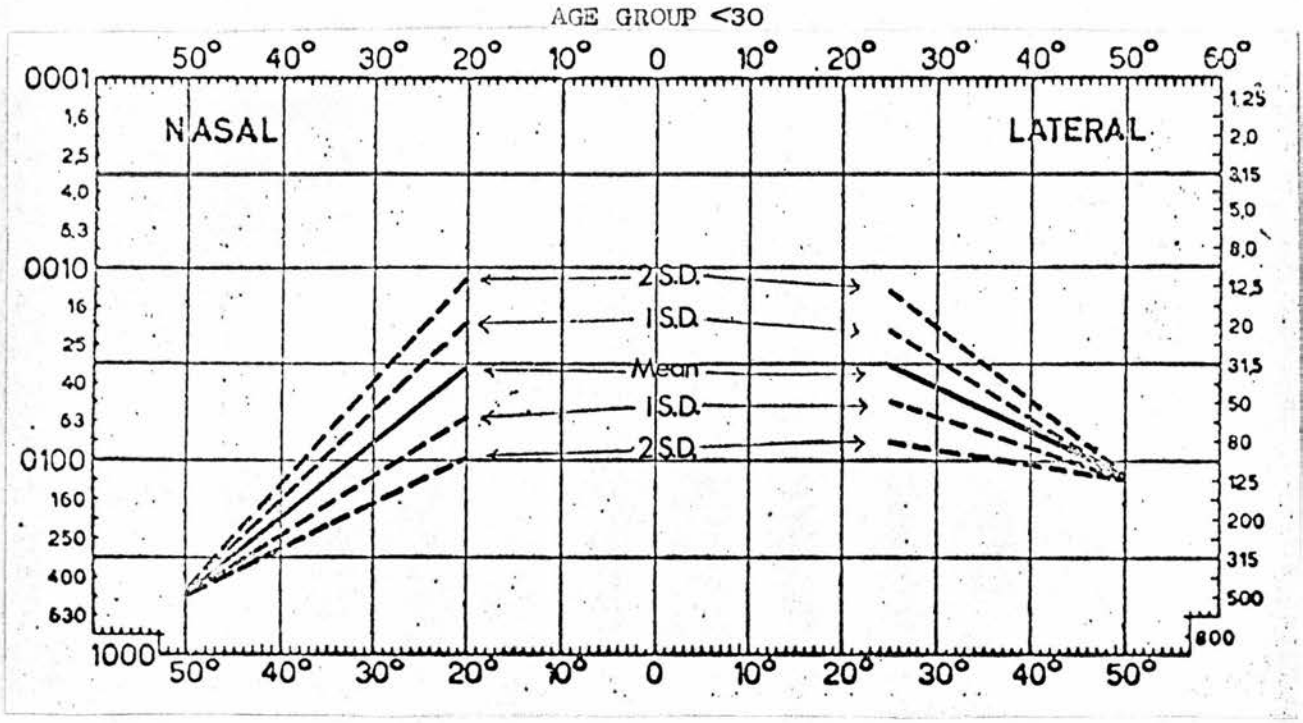
of refraction, are discussed more fully by ASPINALL, (1968). Part of this information, where relevant, will be used to establish the norms under different adaptational conditions.

(iv) Standard Test Conditions: Background Luminance 31.5 asb.

The norms relevant to this test condition were developed by ASPINALL (1968). Over 200 subjects were tested ranging from six years to 86 years. The means and standard deviations are plotted in Figs. 72 to 76 , which show the target intensity at threshold on the ordinate, and the retinal excentricity on the abscissa. (The same method of computing means and standard deviation is used here as the dark adaptation and the photopic luminosity data. The values of light intensity on the ordinate are in logarithmic form. As the physical scale is logarithmic, we assume from Fechner's Law that increments along this scale represent equal visual steps. We thus replace the ordinate values of light intensity by an arbitrary linear scale. The resulting distribution for each retinal position now forms a normal distribution or Gaussian curve about the mean. This method follow ASPINALL (1968) and VERRIEST (1971).)

The standard deviations for different ages are tabulated in Table XV , and an illustration of the increase in the standard deviation with age is shown in Fig. 77 . Tests of the significance of the difference/

VARIATIONS IN THE RATE OF THRESHOLD CHANGE BETWEEN TWO RETINAL LOCATIONS



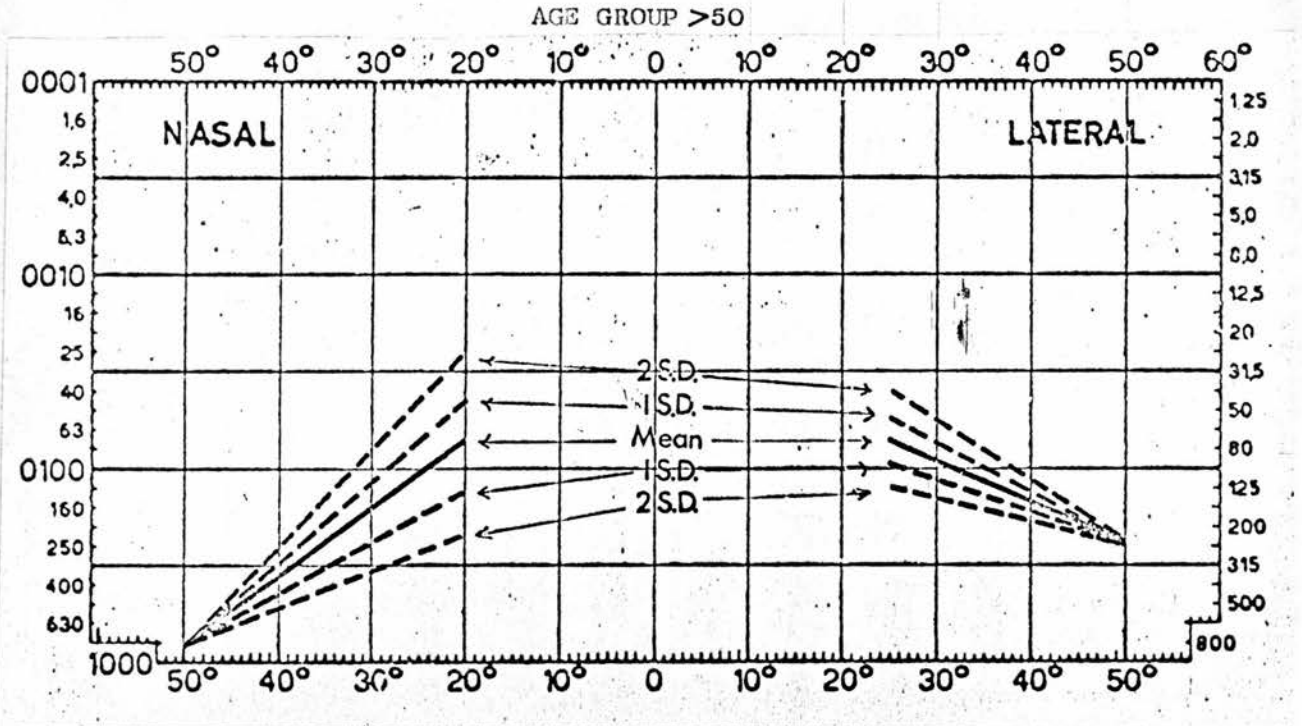


Figure 78

difference between standard deviations (F ratio), showed this increase to be significant in the peripheral retina. The increase in the standard deviation at 20° in the temporal field was confirmed in a homogeneous study of 45 students (ASPINALL, 1968). As this location is adjacent to the blind spot, caution is necessary in interpreting abnormality in the differential threshold at this point.

The standard deviation illustrates the inter individual variation within any age group. However, if we consider two points on one individual threshold gradient, i.e. intra retinal variation, there are also limits to the rate of change of threshold to be expected in a normal retina. For example, if the threshold value for a particular subject at 50° excentricity lies within normal limits, but well above the mean value, it may not be considered normal for this individual's sensitivity at 20° excentricity, although within the normal limits of the group, to be well below the mean. The tolerances to be expected in a normal retina for rate of change of sensitivity are shown in Fig. 78. For:

a.) The age group less than 30 years:-

The average gradient between points 20°N and 50°N makes an angle with the horizontal of $\tan^{-1} 10.7/15$ (approx. 36°). One standard deviation from the mean changes the slope/

TABLE XV

STANDARD DEVIATIONS (LOG UNITS) AT 5 RETINAL POINTS FOR EACH AGE GROUP.

	RETINAL POSITION				
Age (years)	50°N	20°N	Fovea	20°L	5C
Group I 25	0.22	0.16	0.17	0.2	0.
Group II 26 - 35	0.23	0.18	0.12	0.18	0.
Group III 36 - 45	0.16	0.21	0.22	0.30	0.
Group IV 46 - 55	0.21	0.25	0.17	0.28	0.
Group V 55 +	0.10	0.29	0.23	0.29	0.
Mean for total population	0.184	0.22	0.18	0.25	0.

slope by tan $^{-1}$ 2.5/15 (approx. 10°).
The average gradient between points 25°L and 50°L makes an angle with the horizontal of tan $^{-1}$ 5/12.5 (approx. 22°). One standard deviation changes the slope by tan $^{-1}$ 1.1/12.5 (approx. 5°).

b.) The age group greater than 50 years:-
The average gradient between points 20°N and 50°N makes an angle with the horizontal of tan $^{-1}$ 11.6/15 (approx. 38°). One standard deviation changes the slope by tan $^{-1}$ 2.3/15 (approx. 9°). The average gradient between points 25°L and 50°L makes an angle with the horizontal of tan $^{-1}$ 6/12.5 (approx. 26°). One standard deviation from the mean changes the slope by tan $^{-1}$ 2/12.5 (approx. 9°).

In summary, there are two considerations for sensitivity to light in a normal retina. Firstly group variation given by Figs. 72 to 77 , and secondly changes in the gradient of sensitivity shown in Fig. 78. The gradients given above indicate that there is a relatively greater loss of sensitivity in the peripheral retina with increased age than occurs at the fovea.

In an attempt to assess the contribution to sensitivity losses, a multiple regression technique after Doolittle (GUILDFORD page 407) was used./

used. Variables considered were age, acuity (as assessed by an orthorater checkerboard) and pupil diameter. The regression equation for the prediction of retinal sensitivity (variable X_1) at the fovea is:-

$$X_1 = a + 0.0826\ X_2 - 0.336\ X_3 - 0.115\ X_4$$

where a is a constant $\left(a = M_1 - b_{1.2}M_2 - b_{1.3}M_3 - b_{1.4}M_4\right)$ variable X_2 is age; variable X_3 is acuity; and variable X_4 pupil diameter. The M's are the means of respective variables, and the b's the coefficients associated with the variables in the regression equation. Given values of age, pupil diameter, and acuity, the regression equation gives the best prediction for foveal differential sensitivity.

An estimate of the contribution of each variable to this prediction is given by the product of the correlation coefficients and their respective β coefficients. This indicates that age accounts for 39% of the variance in the data, acuity for 12% variance and pupil diameter a negligible contribution of 2% of the variance.

For the peripheral retina (50° temporal) correlations in the homogeneous group showed that refraction ceased to be a relevant variable beyond 30° excentricity. Of the variance in retinal sensitivity at this point, 63% was due to the age variable and 5% to pupil diameter. These results confirmed the increase weight of the age variable in the prediction of retinal sensitivity in/

in the periphery. This finding is in agreement with VERRIEST (1965), and WOLF (1962) using the critical fusion frequency.

(v) High Intensity Background Luminance

The static perimetric profiles obtained under standard test conditions (background intensity 31 asb.) are likely to result from mixed rod and cone function in the peripheral regions. Although rod response is particularly associated with the peripheral retina, it should be possible by manipulating the adaptation level to emphasise the cone response in these regions.

The average values of retinal illumination calculated from the pupil diameters of different age groups, range from approximately 70 to 150 trolands when the background is 31 asb. The unit troland only accounts for pupil diameter changes and does not account for lens opacities occurring with increased age. Consequently, the actual retinal illumination values are in fact even smaller in the old age groups. According to MOON and SPENCER (1945) the luminance of 31 asb. is considerably lower than the level for which $\Delta L/L$ is constant under Weber's Law. At this level of luminance, the photopic luminosity curve shows an increase in sensitivity to short wavelengths (WEALE, 1953), indicating the activity of the scotopic function in peripheral regions. Thus under standard Goldmann adaptation conditions, thresholds result from mixed rod/cone function./

function. Estimates of the level of retinal illumination at which rods no longer play a differential role in wavelength response are given as 1,000 trolands (ANGUILAR and STILES, 1954; NIMEROFF, 1964).

It was decided to change the light source in the Goldmann Bowl so that a retinal illumination level of approximately 1,000 trolands could be reached, and then to test experimentally whether the response from the peripheral retina was of the rod or cone type by using a variation on the normal dark adaptation experiment.

A lamp holder was built so that a tungsten iodine lamp (100 w. 12 v.) could be fitted into the normal Goldmann fittings, and readily interchanged with the standard Goldmann lamp (45 w. 6 v.). Springs were fitted below the plate holding the lamp, so that the position of the filament could be adjusted by a screw-driver to fit the optical characteristics of the test spot projection system. A voltage supply with a thermostor was constructed, to avoid initial current surges being applied to the lamp, and the unit was run from a stabilised mains supply. A fan cooling system was incorporated to prevent excess heating of the lamp. Measurements of the bowl intensity with the lamp in position showed that the level of 1,000 trolands could be reached with a 2.7 mm. diameter pupil.

The experimental method used to test the relative/

relative contribution of peripheral rods and cones was as follows. Under normal conditions of dark adaptation measurement, the test procedure consists in preadapting the eye to a high luminance. This is followed by a period of total darkness, in which the recovery of visual sensitivity to a small test target is measured. The normal dark adaptation curve in a peripheral retinal region follows the biphasic curve as in Fig. 79. The first portion of the curve represents the cone response, and the second the rod response. (Evidence for this assumption is given in Section III).

It has been established that, whatever is the exact nature of the dark adaptation process, there is a close correspondence between differential thresholds and thresholds obtained during dark adaptation, (CRAWFORD, 1934, 1947). It is possible, therefore, to preadapt the eye to a high luminance, as in standard dark adaptation tests, but instead of following the recovery of sensitivity to total darkness, to follow the recovery of sensitivity of the test target against a constant background light. In effect one is measuring the changes in the differential threshold $\Delta L/L$ against time. Adaptation curves generated in this manner will reflect the relative sensitivities of rod and cone processes at different stages of adaptation and at different levels of the constant adaptational background. In order to/

Figure 79

Dark Adaptation Curves at 3 retinal points

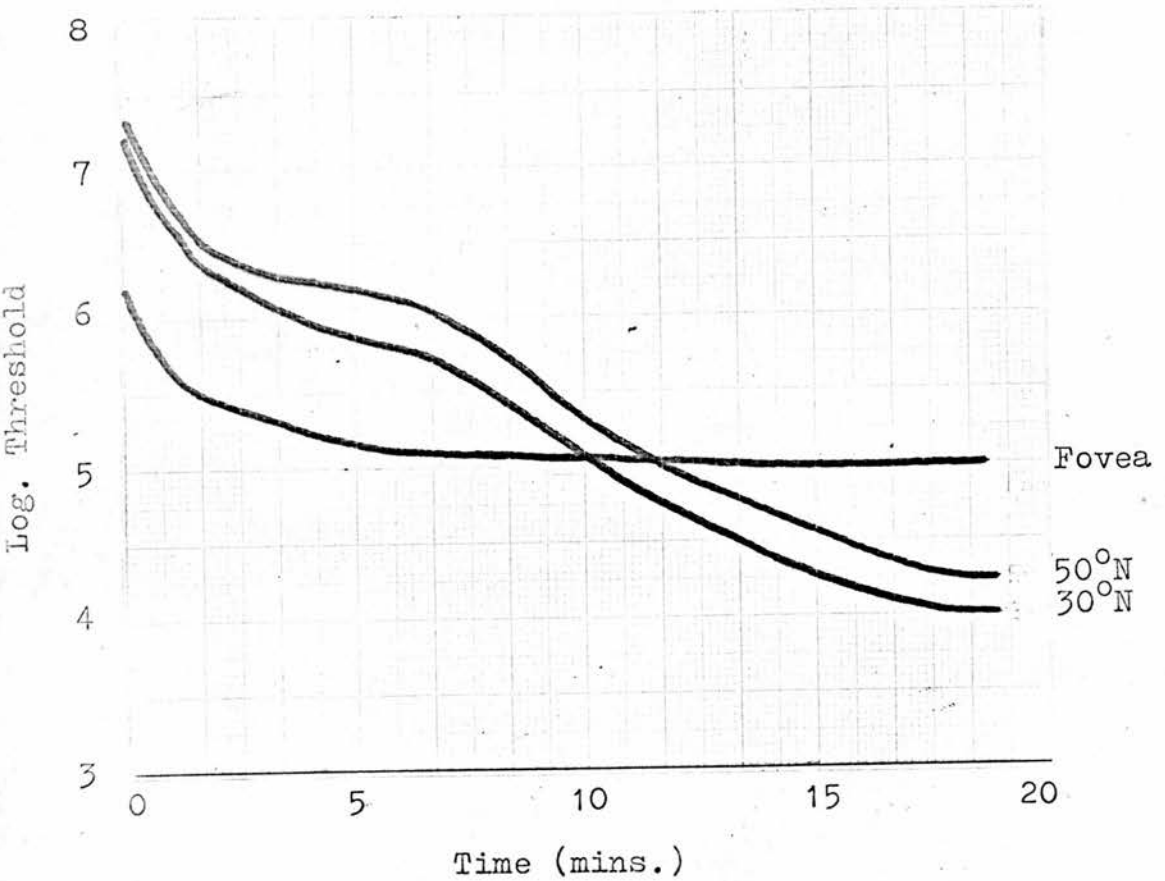
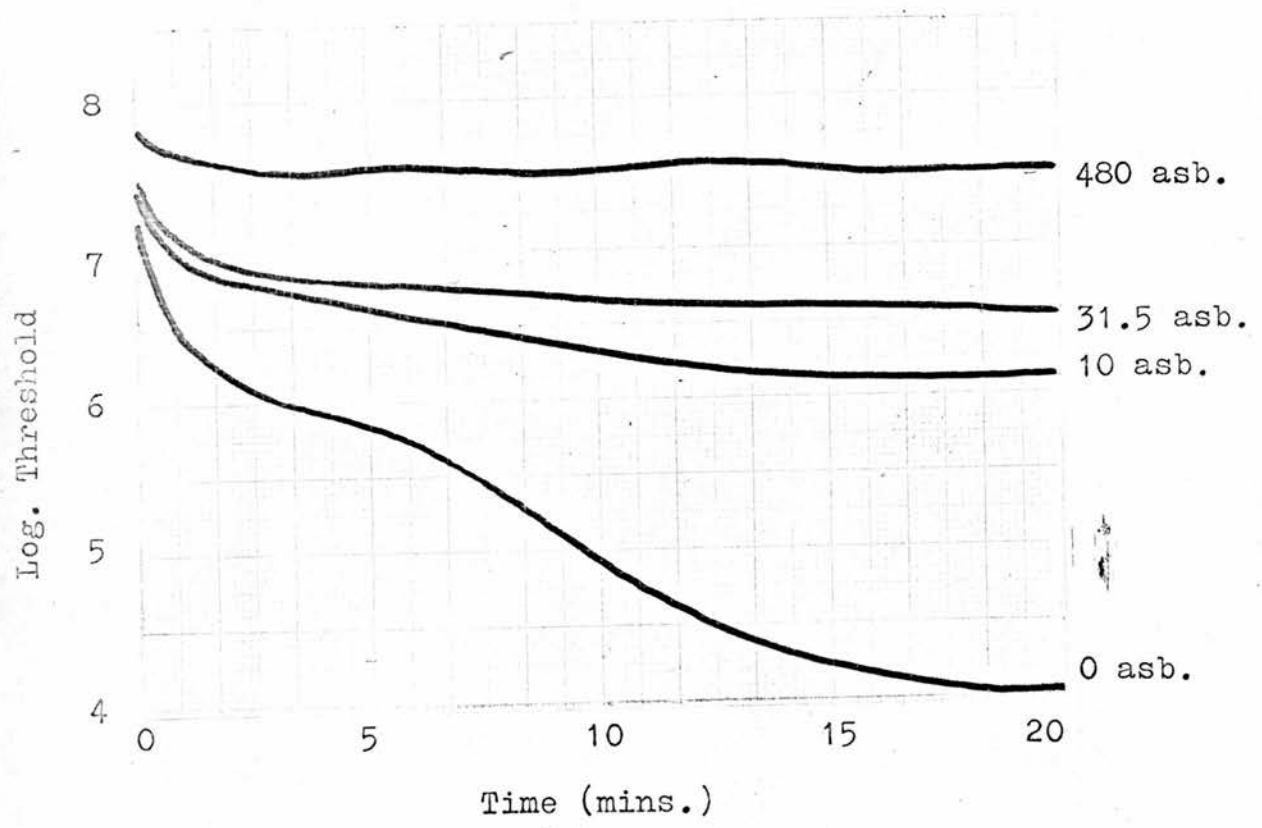


Figure 80

Adaptation to 4 different backgrounds (30°N)



to carry out this measurement the Goldmann Weekers adaptometer (see page 254) was used in conjunction with the Goldmann perimeter. In the measurement of differential thresholds following preadaptation, the adaptometer was used as preadaptation source, and the perimeter as a means of assessing $\Delta L/L$ against time, at any retinal position.

The preadaptation intensity was 16,000 asb. for a period of five minutes. The Goldmann $\frac{1}{4}$ mm.^{2} target was used as test target, as this was the target selected for static perimetry. The adaptation curves were obtained against four background intensities of the Goldmann bowl:- one at zero background; one at a background of 10 asb; one at 31 asb. (standard bowl conditions); and one at 450 asb. using the new light source. Measurements were taken at 0°, 20°, and 50° excentricity in the nasal field.

With no background light in the bowl dark adaptation curves to white light are shown in Fig.79 at three retinal locations. The curve is in accordance with the classical view of the dark adaptation process as dependent on two mechanisms. At 30° and 50°N, where there are cones and rods, the cone plateau representing the sensitivity of dark adapted cones is around 7.0 intensity units. At around six minutes after preadaptation, the rods take over, and sensitivity reaches 5.0 units after 20 minutes in the dark. At the fovea, in a presumably/

presumably rod free area, only the first part of the curve is present indicating only one functional systen in this area.

The curves in Fig.80 show the adaptational changes in Δ L/L to four different background intensities, using the same preadaptation and target conditions as in Fig. 79. All curves were obtained at 30° excentricity. What is particularly surprising in Fig. 80 is that the addition of a small amount of light to the bowl has a marked effect upon the changes of sensitivity against time. At a background of 10 asb. there is only slight evidence of a second rod segment to the adaptational process. At this background intensity, therefore, the rod system is only slightly more sensitive to the white target than the cone system (i.e. the plateau indicating maximum cone sensitivity is only slightly above that indicating rod sensitivity at 20 minutes). In the two curves for backgrounds of 31.5 and 480 asb., the experimental variation in the thresholds are of the same order as any differences between rod and cone systems that might exist. Differences, if they existed, would therefore be undetectable. (Note however, that there is a general raising of thresholds at 480 asb. Secondly, the target thresholds form almost a straight line from the moment the preadaptation light is switched off. In other words the sensitivity immediately upon entering the bowl is similar to its level after 20/

20 minutes in the bowl. A more gradual adaptation was noticeable at a background of 31.5 asb.)

The information in Fig.80 shows basically two features. Firstly, the addition of a small amount of light to the bowl drastically reduces rod sensitivity in the peripheral retina, and makes the rod and cone sensitivities for a particular retinal region almost equivalent. Further additions of white light to the bowl produce adaptational curves which only have one segment within the experimental error of the method. This could arise if either cones and rods had the same sensitivity, or if cones were more sensitive than rods. The data does not allow us to distinguish between these possibilities. For the two background intensity levels at which this occurs, one is lower than the calculated retinal illumination level at which only cones will function, and one is higher.

In order to clarify this position, two further experiments were carried out. A variation on the two filter analysis of the dark adaptation process (see Section Vb) was used for:-

a.) a series of experiments in which $\Delta L/L$ was assessed for two wavelengths against the time to adapt to the four different background intensities.

b.) a series of experiments in which the background intensity of the bowl was used as preadaptation/

preadaptation level, and the cone/rod interaction measured immediately after preadaptation ceased.

Experiments under a.)

In the first series of experiments a red and yellow filter were placed in turn over the test patch. These filters were selected so as to avoid the spectral region of macular pigment absorption (See Fig. 37). As shown in Section Vb, the separation between the dark adaptation curves for two test stimuli reflects the contribution of rod and cone participation in the adaptational process. One characteristic separation indicates cone activity, and another characteristic separation indicates rod activity. As the adaptation process progresses, the separation changes from that representative of cone function, to that representative of mixed cone/rod function, then to that representative of purely rod function. It should be possible, therefore, by measuring the threshold separation between the two wavelengths to determine whether it is cones, or rods, that are responsible for vision at a particular level of background intensity. Furthermore, it is possible to compare the functioning of peripheral and foveal cones by measuring the characteristic cone separation in the fovea, and in the peripheral retina.

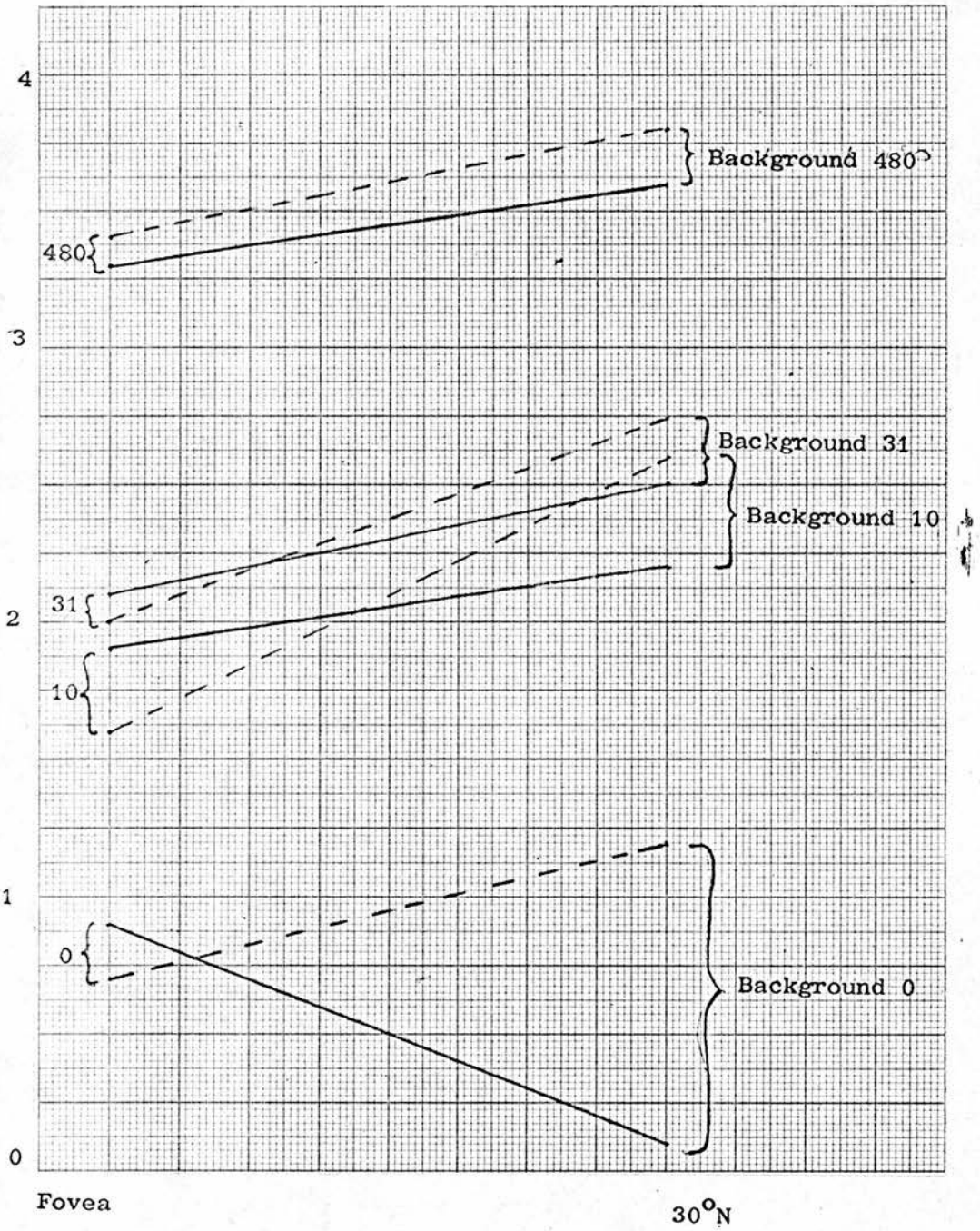
The average separation between the cone function for the two filters against a dark background at/

at 30°N was 0.2 log units. The rod separation for the same two targets was 1.3 log units. The curves cross over during dark adaptation so that initially the yellow is above the red, and finally the yellow is below the red. The cone separation at 30°N was found to be equal to the separation between the dark adapted foveal thresholds for the same targets. Thus the separation for peripheral cones is the same as that for foveal cones. This suggests that the spectral sensitivity of foveal and peripheral cones is the same. This comparison is only possible if the filters are chosen so that macular pigment absorption, which would only affect the foveal cones, is avoided. This finding is supported by STILES (1953) using monochromatic test targets, and WALD (1960) using relatively broad band filters.

The equivalence of the foveal and peripheral dark adapted cones is particularly useful from the experimental viewpoint. Instead of requiring a series of dark adaptation runs to find both cone and rod separations, the following technique is used. The final dark adapted thresholds for both targets are measured at 30° excentricity. This gives the characteristic rod separation. The cone separation at 30°N is obtained by measuring the dark adapted foveal thresholds for the two targets. In absolute terms, the cone thresholds at the fovea and at 30°N will be different, but in relative terms the separation will be constant. The same/

Figure 81

Relationship between thresholds for red and yellow targets at the Fovea and at 30°N against 4 background intensities.



same principle was used to establish the cone and rod separations of Δ L/L for the further four background luminance levels. These are shown in Figs. 81 and 82.

In Fig. 81 the relationship between the foveal thresholds for the red and yellow targets is shown at the left, for the four different background intensities. The red threshold is below the yellow for the lowest three intensities but above the yellow at the highest background intensity. The characteristic separation for the dark adapted cones is 0.2 log units. This separation is maintained at a background of 10 asb. but changes slightly for the two highest intensities. The right hand threshold values are taken at 30°N excentricity at the same four background intensities. Readings were taken after twenty minutes adaptation to the appropriate background. At zero background the separation is 1.3 log units with the red thresholds above the yellow. However, at 10 asb. the separation has dropped to 0.4 log units. At 31.5 asb. the separation is 0.3 log units, and at 480 asb. it is 0.2 log units. If the spectral sensitivity of foveal and peripheral cones is the same, the critical point at which peripheral thresholds can be assumed to be determined by cones, occurs at the background intensity at which the separation between the two targets corresponds to the foveal separation.

It is apparent in Fig. 82 that the threshold/

Figure 82

Threshold Separations for red and yellow targets at 4 background Luminances.

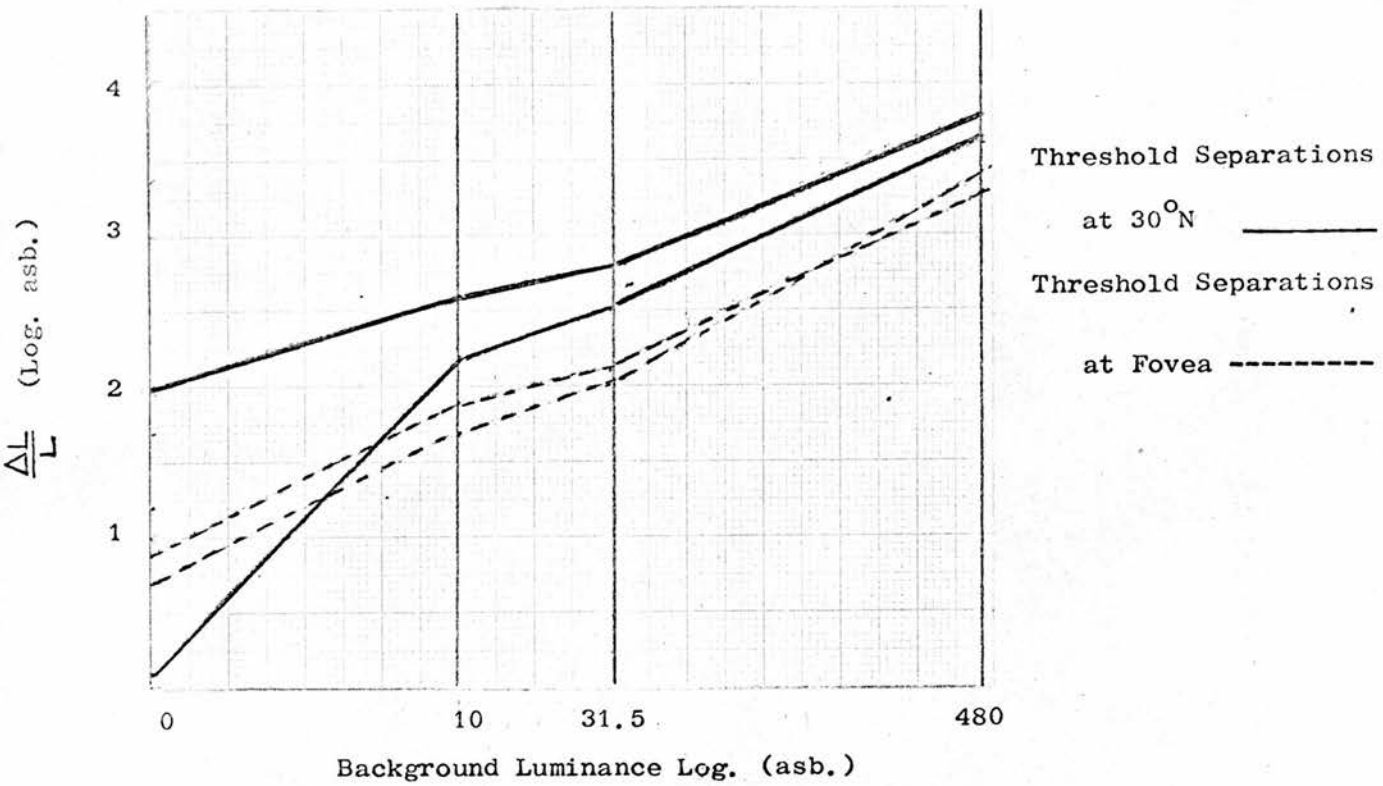
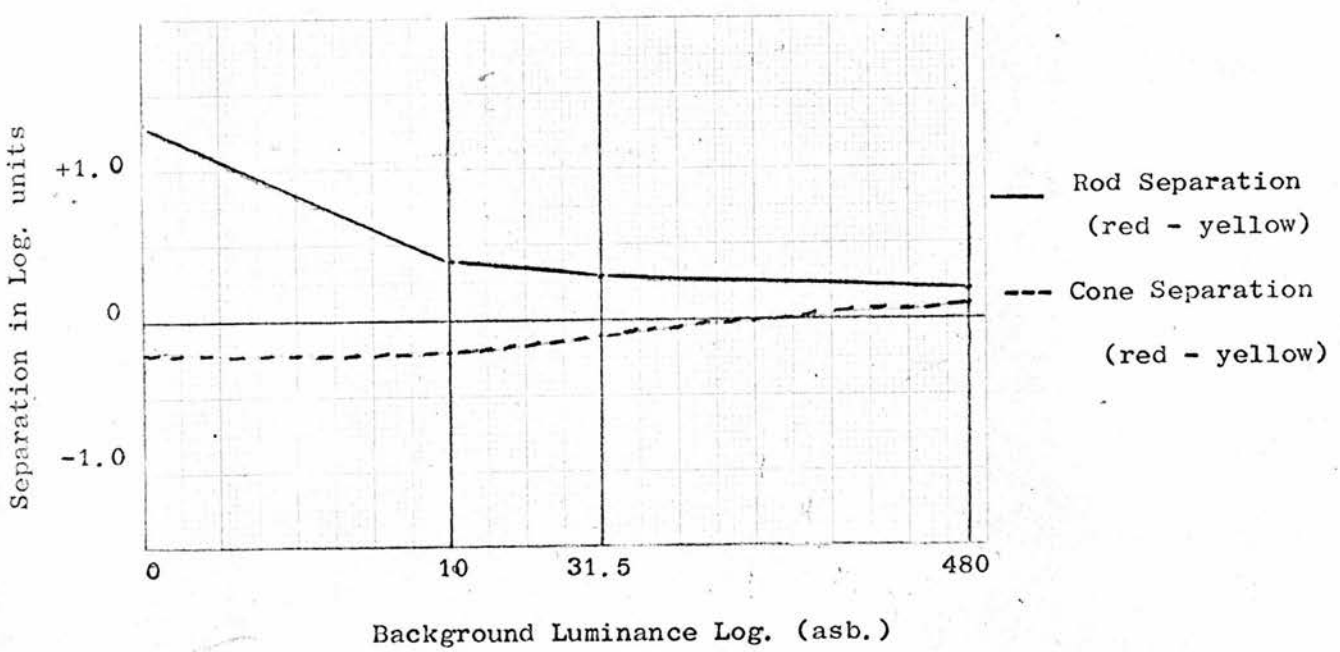


Figure 83

Changes in rod and cone separations at different background Luminances

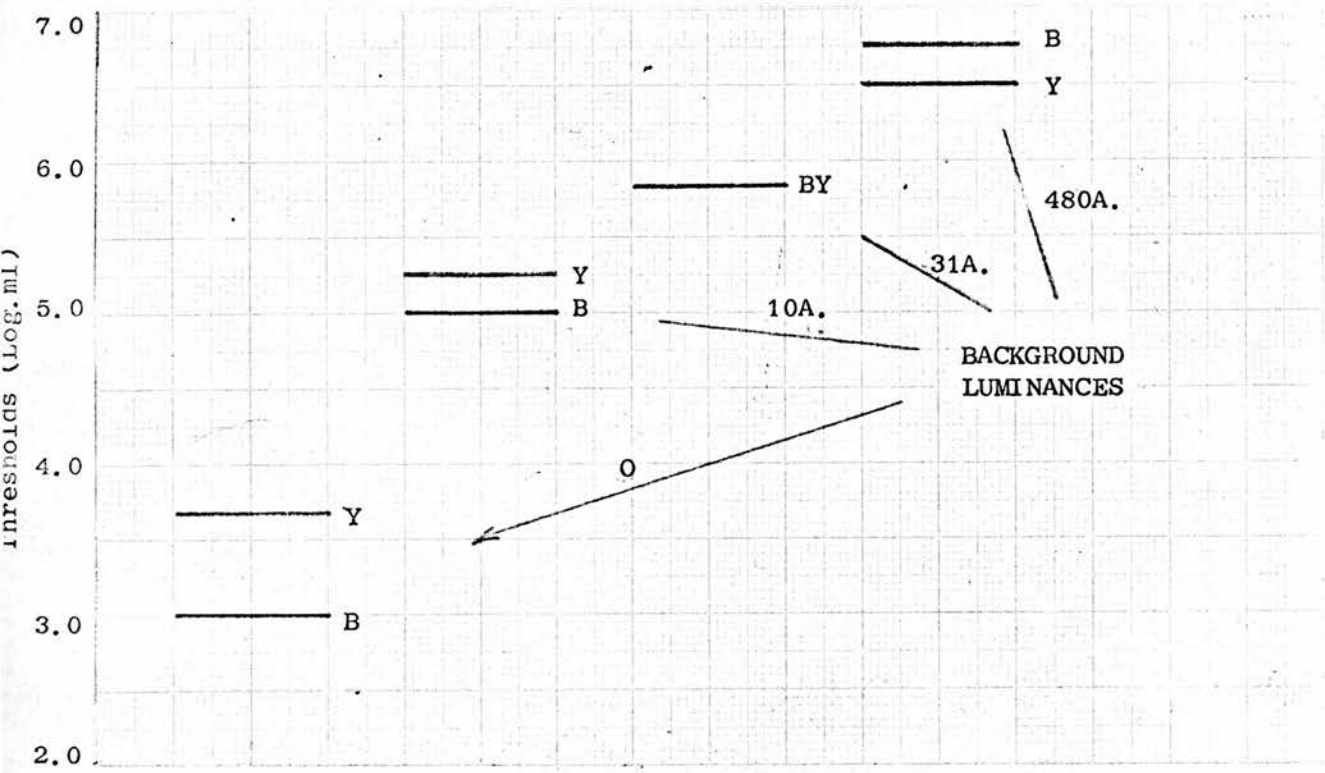


threshold separation at 30°N is much larger than the foveal separation at the two lowest background intensities. This corresponds with the marked second phase of the dark adaptation process at zero background, and the slight evidence for rod activity at 10 asb. shown in Fig. 80 . At 31.5 asb. where Fig. 80 shows no evidence of a rod segment, Fig. 81 shows that the separation at 30°N is still larger than that at the fovea. indicating the presence of rod activity at this level of background intensity. (The Wilcoxon matched pairs test was used to check that the separations between foveal and peripheral thresholds were significantly different over a number of individual threshold determinations). At 480 asb. background the curves have drawn together so that the difference between the separations is now 0.1 log units. This difference between the foveal and peripheral threshold separations was not significant using the Wilcoxon matched pairs test. This is further evidence, therefore, that at the highest background intensity the separation between target thresholds is characteristic of cone activity at 30°N.

Data on luminance difference thresholds, shows remarkable constancy over medium and high luminance levels (CRAWFORD, 1937) which results in the Weber-Fechner Law. However, inspection of Figs. 82 and 83 shows that even in the foveal thresholds, there is a reversal in target/

Figure 84

Threshold levels for Blue and Yellow targets at 30°N immediately following preadaptation to the 4 background intensities.



target sensitivity at the highest background luminance. This might be explained because the Goldmann Projection system projects a light spot onto a background, and so produces an additive mixture of light within the test target. Thus while the dark adapted foveal thresholds are obtained for a narrow band red and yellow target, the light adapted foveal thresholds are obtained with a desaturated red and yellow target. This would particularly affect the red target, (as the background light was white) and could explain the change in sensitivity at 480 asb.

Experiments under b.)

As a final test of the method, a second series of experiments was carried out in which the eye was pre-adapted in turn to the four background luminances (0, 10, 31, 480 asb.) of the Goldmann Bowl. The early stages of dark adaptation (i.e. immediately after preadaptation) were measured to the yellow and blue/green filters as in Section Vb. (An explanation of the method is given in Section Vb , and the characteristic rod and cone separations for the blue/green and yellow filters are given in Table XVI). The length of preadaptation was five minutes, and the thresholds to the two filters were measured against a dark background, as in the normal dark adaptation experiment. The results are shown in Fig. 84.

With no background preadaptation, the separation/

separation is characteristic of rods. Following 10 asb. preadaptation the blue/green thresholds are below the yellow but the separation is reduced, indicating a mixed rod/cone response with rods predominating. Following 31 asb. preadaptation, the thresholds for blue/green and yellow coincide, indicating mixed response at this level. Following 480 asb. preadaptation, the blue/green threshold is raised above the yellow, indicating predominantly cone response at this background intensity.

It would appear, therefore, that:-

1. if static perimetry is carried out against a dark bowl, a normally functioning rod system is necessary to obtain a normal threshold gradient.
2. At 10 asb. where rods are still slightly more sensitive than cones, a normal gradient depends upon normal rod activity. However the gradient is only slightly reduced if norrods function, but cones function normally.
3. At 31 asb., where there is no evidence of rod function in Fig. 80 (the Fig. indicates that rods and cones have the same sensitivity at this background luminance) a normal threshold gradient would be obtained if either normal rod, or normal cone function existed, or both. Conversely, a normal threshold gradient can/

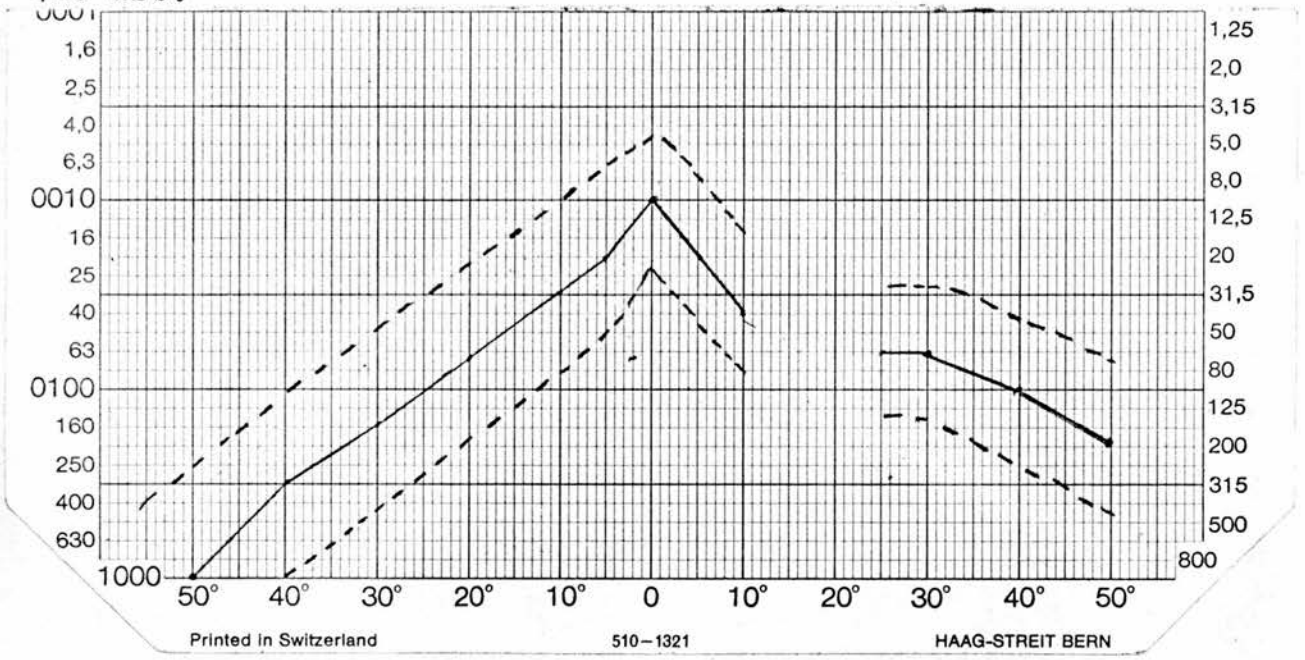
can be obtained at this background luminance in a situation where there are no functioning rods, or where there are no functioning cones. Similar conclusions have been reached by SLOAN (1950, 1971) in which she states "The success of conventional perimetric techniques (i.e. perimetry in which the adaptation levels are frequently in the mid-range) is to a great extent dependent upon the fact that both cones and rods are affected in most eye diseases."

4. At the highest background level (480 asb.) where cones are more sensitive than rods, a normal threshold gradient depends upon the functioning of cones.

It has been shown by a series of different experiments, that there are reasonable grounds for believing that static perimetry at high intensity backgrounds will provide a measure of cone activity in peripheral regions of the retina. SLOAN (1971) has recently advocated that instead of raising the adaptational level to emphasise cone vision, the replacement of white by red targets will achieve the same result. The substitution of white by red targets, at an adaptation level where rods and cones have equal sensitivity to white targets (i.e. around 31 asb.), should make the cones more sensitive to a red target than the rods. It is clear that for a comprehensive approach to visual field/

Figure 85

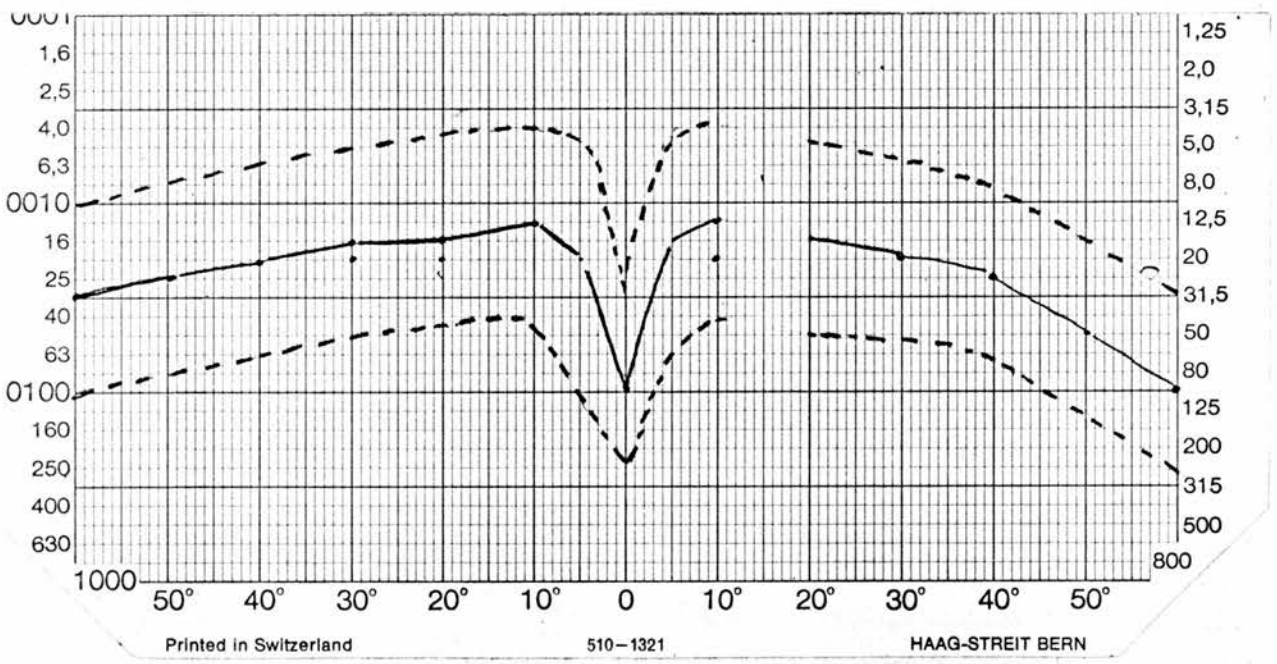
Mean Threshold Gradient for Age < 30 years at Background Luminance 480 asb.



Retinal Excentricity

Figure 86

Mean Threshold gradient for Age < 30 years at Zero Background Luminance.



Retinal Excentricity

field testing either method can be used, in conjunction with perimetry at a lower adaptation level, or under completely dark adapted conditions. The experiments have shown that it is possible to study independently, the functioning of rods or cones in any retinal region.

Norms

Finally, the norms for the high intensity threshold gradient and low intensity threshold gradient are shown in Figs.85 and 86. The norms at high intensity are very similar in shape to those obtained under standard Goldmann conditions. The individual variation is the same, but the slope of the threshold gradient is slightly steeper and more peaked towards the fovea.

The static perimetric norms against a totally dark background are of a completely different shape, and represent scotopic thresholds across the retina. In this case the individual variation is greater than when the thresholds are measured against a constant background luminance.

These results were based on a young age group. Age studies were not carried out at the highest and lowest intensity levels. However, as these intensities were chosen so as to reflect cone and rod activity, the age variations in cone and rod thresholds can be extrapolated from the dark adaptation studies of age variation. See Table XVI for age changes in the final threshold (rods) and in the dark adapted cone thresholds. These/

These changes will be added to those in Figs.85 and 86 for the limits of normality at older ages.

(vi) Test Procedure

The method of examining the threshold gradient was the same for all adaptational conditions. The only variation was in the time of adaptation to the bowl before testing started. For the test conditions where the bowl luminance was equal to 31 or 480 asb., five minutes of preadaptation was given. As Fig. 80 shows, the differential threshold is stable after five minutes in both cases. For the scotopic thresholds an adaptation time of 20 minutes was used. Again Fig. 79 indicates that the thresholds are only beginning to stabilise after this period of dark adaptation.

Standard test conditions were as follows. The subject was told the form the examination would take, and was seated before the instrument until the eye to be tested was at the centre of the telescope crosswires. The appropriate adaptation was then given. The subject was instructed to look directly ahead at the centre of the bowl (or red fixation spot in the case of scotopic thresholds). He was asked to tap on the table immediately he became aware of a light in the bowl. (This method has been found to be more satisfactory for reproducable results than an oral response. Firstly, a more positive response is initiated, and secondly any slight movement/

movement of the chin, which would alter the position of the eye with relation to the telescope crosswires, is obviated). The test spot was shown at the location to be tested. Neutral density filters were then placed in the light path until the test spot was below threshold. Gradually these filters were adjusted so that the intensity of the test object was increased in steps of 0.1 log units until the threshold value was obtained. The procedure was repeated three times at the same point on the meridian, each presentation of the test spot lasting approximately two seconds. The interrupter was set to the off position, so that any eye movements which occurred between the presentations of the test spot did not give additional clues to the test spot intensity.

The procedure by which the subject is given prior knowledge of the test spot position before thresholds are measured is debatable. Its purpose in the present context was to decrease the uncertainty of the subject in the test situation, and consequently to increase the reliability of the test. (Most patients were new to the test situation). For complex stimulus/background relationships it appears that foreknowledge facilitates detection (ENGEL, 1971; GRINDLEY and TOWNSEND, 1968). However, where the test spot is circular, and the background homogeneous, MERTENS (1956) has suggested that knowledge of the test spot position has no influence/

influence upon the detection probability of an isolated target.]

After two or three trials, the full examination of the meridian took place, the subject being given rests after every three threshold determinations. Measurements were only taken when the subject fixated properly. As a general rule, readings were taken at 50°, 40°, 30°, 20°, 10°, 5° in the nasal and temporal fields, and at the fovea itself by means of the four fixation spots. The pupil diameter was measured at the beginning and at the end of the testing session.

In cases where perimetric profiles were obtained at high and at zero background intensities on the same patient, the high intensity measurement was always measured first. This was to encourage the subject to fixate properly under conditions in which the eye movements could be observed. Although the subject was not made aware of the fact, there was no facility for observing eye movements during scotopic threshold measurements.

2. Dark Adaptation

(i) Description of the Instrument

The basic instrument available for this study was the Goldmann Weekers Adaptometer of Haag Streit Liebefeld. Several modifications were made to this instrument which will be described shortly. The standard instrument is/

is described first.

This instrument has three principal features: one is for light preadaptation, the second is for measurement of visual sensitivity, and the third is for recording the results. Preadaptation in the standard instrument is achieved by two lamps which illuminate the inside of a white spherical bowl. Variations in preadaptation are made either by substituting bulbs of different wattage, or by changing the length of the preadaptation time. The light source for the test patch is situated at the back of the instrument. This is maintained at a constant intensity rate by stabilising the voltage supply and by under-running the bulb.

Control of the amount of light falling in the test area is achieved by several devices, which can be inserted separately or in any combination in the light path. The initial test patch luminance is set at maximum by the adjustment of a diaphragm. The test patch light illuminates a translucent screen which can be measured by a mobile luxmeter. Reduction in the brightness of the translucent screen, from its maximum value, is obtained in a continuous fashion by a neutral wedge, which can be inserted in the light path and manipulated by a control knob. Its value at any position is shown on an illuminated screen and on a revolving drum in the recording system. The test patch light can be presented either for an unlimited time, or in a/

a sequence of on/off flashes. This is effected by means of a revolving diaphragm rotating in the light path at one revolution per two seconds.

Finally, the recording section of the instrument provides the experimenter with a graph of the threshold intensity (in log units) against time (in minutes). A revolving drum to which graph paper can be attached, provides the time variable. The logarithmic intensity scale has a range of seven log units covered by the neutral wedge. A fixation light with an adjustable brightness rheostat is also provided, together with uniform diffusing screens, striped diffusing screens or Landolt C charts as variable test plates. The largest of the available test patches subtends an angle of 11° when the chin is placed in the chin rest.

The choice of test patches enables different criteria to be used for threshold measurements. Controls exist so that if the stripes are used, they can be rotated into any position. In this case the subject can be asked to turn a knob to rotate the stripe into a horizontal or a vertical position. The position is shown on the illuminated dial. The experimenter can also rotate the stripe without the subject being aware that he has done so. With the uniform screens as test plates, the normal method of limits can be used so that the patient responds present or absent to the variations in luminance. On the standard instrument changes in/

in test patch intensity are controlled manually, so that if the test patch brightness is to be increased at a constant rate, the neutral wedge control knob must be turned by the experimenter at a constant rate. The lamp used for the preadaptation and for the test patch illumination are continuous tungsten sources each with a colour temperature of 2860°K. Consequently, in normal dark adaptation measurements, the preadaptation is to white light, and the subsequent measures of visual sensitivity are to white light.

(ii) The Dark Adaptation Process

The typical dark adaptation curve obtainable on this instrument is of the form shown in Fig. 80 . This classical experimental demonstration of the dark adaptation process was first shown by AUBERT (1865) and confirmed by HECHT (1921) and KOHRAUSCH (1922). The close association of the two segments of the curve with rod and cone function, and with visual pigment regeneration is discussed on page 40.

Theories which have been advanced to explain the loss of visual sensitivity following preadaptation, have concentrated either on the reduction in strength of the visual signal, or the loss of the visual signal in noise. The former group of theories subdivides into photochemical (e.g. HECHT (1929) and more recently WALD's (1954) compartment hypothesis in which the loss/

loss of visual sensitivity is due to the bleaching away, or to the inactivity of rhodopsin); and the neural adaptation theories (e.g. LYTHGOE, 1940; CRAIK and VERNON, 1941; ROSE, 1948; which more readily explain spatial summation effects and changes in sensitivity by neural factors). With the second type (i.e. noise theories) Barlow's name is particularly associated. Here the sensitivity loss following preadaptation is brought about by the light adaptation raising the background of spontaneous activity, so that a visual signal which was previously detectable is now lost in noise.

As the various theories depend upon plausible but often untested premises, there are still various points in favour of each type, and there is too little evidence to choose between them. However, it does appear that the simple photochemical theory or simple neural theory is inadequate (BARLOW, 1964). Measurements of pigment regeneration rates and visual thresholds (RUSHTON, 1965) would appear to show that the threshold is determined by the number of pigment molecules in the bleached state. In addition, psychophysical data (CRAWFORD, 1937, 1947) indicates that different dark adaptation curves can be reduced to one single curve representing the change of "equivalent background light". Both findings are in keeping with some type of noise theory. For an illustration of a typical model of the dark adaptation/

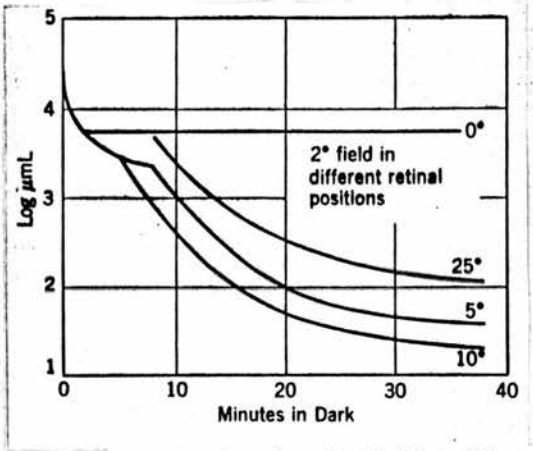
adaptation process based on a concept of molecular structure(after WALD et al, 1963), see CORNSWEET, 1971 p. 127.

(iii) Variables affecting dark adaptation

As with other tests of visual function, whatever visual process is being assessed is defined operationally in terms of the test variables used to measure it. It is not surprising, therefore, that dark adaptation curves depend upon the particular combination of these variables, and that they are sensitive to changes in any one of them. The variables affecting dark adaptation are:-

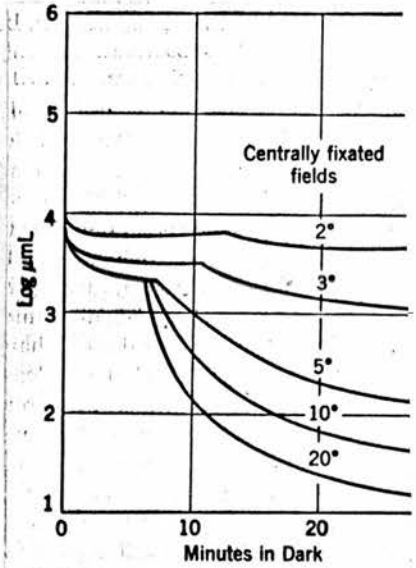
1. Preadaptation light:
    a. Intensity
    b. Duration
    c. Retinal subtense and position
    d. Colour
2. Test Patch
    a. Retinal position
    b. Size
    c. Form
    d. Colour
    e. Duration

The state of eye prior to light adaptation has also been shown to affect the subsequent dark adaptation curve, (WOLF et al, 1960). Examples of the typical changes brought about by some of these variables are/

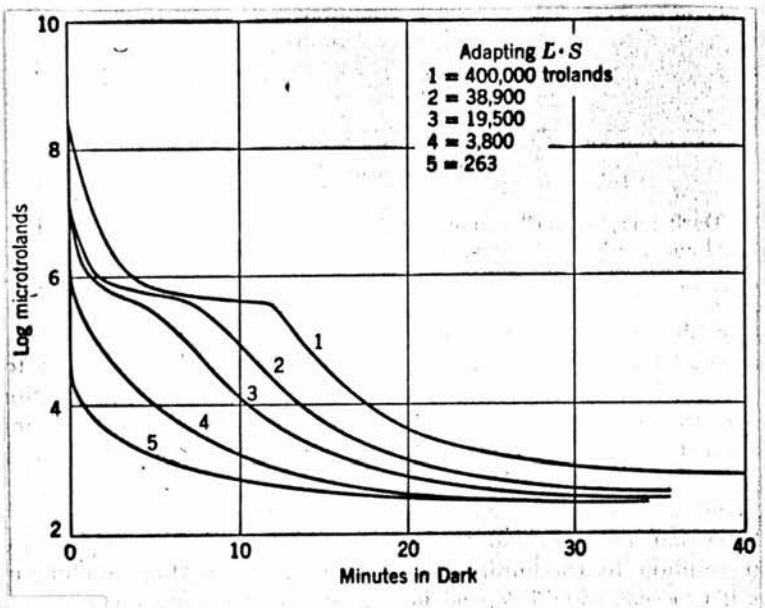


Dark adaptation for Subject SH as measured with a 2° test object placed at various angular distances from the fixation point. (From Hecht, Haig, and Wald, 1935; after Bartley, 1951.)

Figure 87



Dark adaptation for Subject measured with centrally fixated areas of size. Sizes in degrees of visual angle as in (From Hecht, Haig and Wald, 1935; after 1951.)



Dark adaptation thresholds as measured with violet light following preadaptation to different luminance levels. (From Hecht, Haig and Chase, 1937; after Bartley, 1951.)

Figure 88

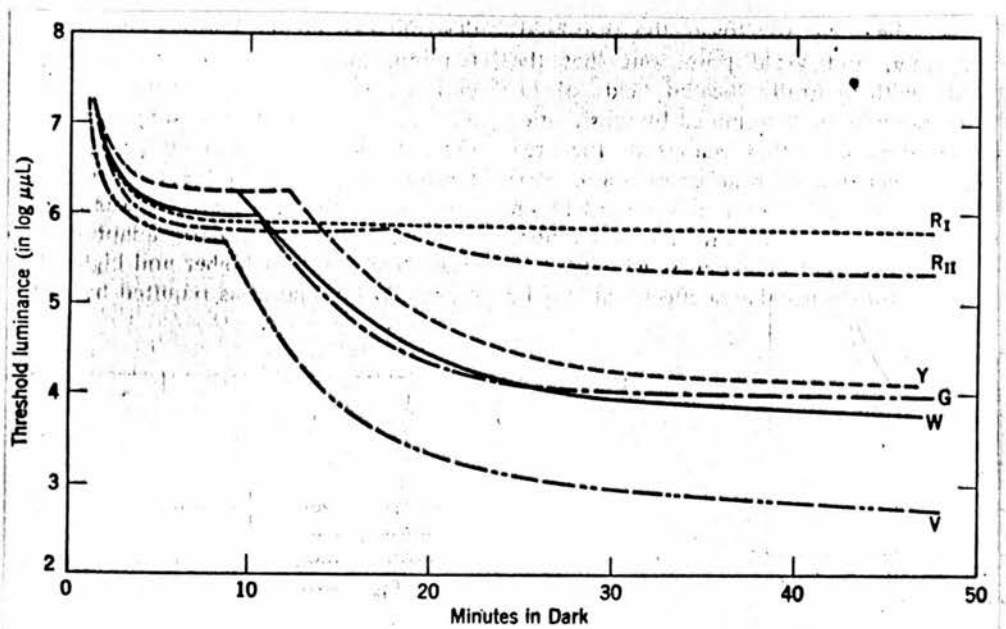


Figure 89

Average dark-adaptation curves for four color-normal subjects as measured with six test flashes of different color. Letters refer to colors whose wavelengths are described in the text. (From Chapanis. Reprinted by permission of The Rockefeller Institute Press, from *The Journal of General Physiology*, 1947, 30, 423–437; Fig. 9, p. 434.)

are shown in Figs. 87 to 89.

There is a close relationship between the effect of luminance and the duration of preadaptation. Up to 3,320 ml. sec. the product of time and luminance determines the subsequent thresholds (MOTE and RIOPELLE, 1953). When the product is larger than this, luminance appears more important than duration until finally luminance is the critical variable and time has no effect on subsequent thresholds. This presumably occurs when the rates of bleaching and regeneration of pigment exactly balance each other.

The general effect of increasing luminance raises the whole dark adaptation curve and prolongs the cone segment(Fig. 88). In addition the α point, or cone/rod break is accentuated at high luminances. Results at different retinal positions and for different stimulus sizes are shown in Fig 87. With centrally fixated fields the α point is accentuated with increased size of test stimulus. Finally in Fig. 89 the effects of wavelength changes in the test stimulus are shown. Again the rod section is accentuated when short wavelengths are used in the test patch.

The effect of changes in the colour of the pre-adapting light do not appear to be marked, unless narrow band stimulation is used at very high luminance, or light from the ends of the visible spectrum is used. MANDELBAUM and MINTZ (1941) showed that in general/

general the foveal cone threshold curves were unaffected. However, pre-exposure to violet light had a greater detrimental effect on the sensitivity to a violet test patch and pre-exposure to red light had a greater effect on the sensitivity to a red test patch. Again LOWRY (1943) claimed that the brightness of pre-adaptation was the only important factor in subsequent rod function. However several authors have stated that dark adaptation is quicker following red pre-adaptation (ROWLAND and SLOAN, 1945; HECHT and HSIA, 1945; FLAMANT, 1946). It would appear therefore, that over wide ranges of colour changes in preadaptation, no appreciable effect is detectable in both rod and cone thresholds. It is brightness which is the dominant factor. A full discussion of stimulus factors influencing dark adaptation is given by GRAHAM et al (1966, page 185).

Of the observer variables, age is predominant in normal population studies. Reference to pupil diameter and lens absorption has been made under the general discussion of age changes in Section IVb. However, there are one or two further findings which have a bearing on the present study, and upon which some of the new modifications have been based.

A significant decline in the sensitivity of the dark adapted eye with increased age has been noted by several authors (HECHT and MANDELBAUM, 1939; ROBERTSON/

ROBERTSON and YUDKIN, 1944; SLOAN, 1947; BIRREN et al, 1948; BIRREN and SHOCK, 1948; McFARLAND et al, 1960; GUNKEL and GOURAS, 1963; JAYLE et al, 1950). While pupil diameter has a marked effect, there are still threshold changes with age when the pupil variable is eliminated (SLOAN, 1947; BIRREN et al, 1948). In addition to the effect of lens changes with age (see page 118), JAYLE et al, (1950) have shown that degenerative and metabolic changes are present and could influence dark adaptation. It appeared from these studies that the most marked change with age wasiin the final dark adapted thresholds. The cone thresholds were changed with age but not as much as the final thresholds. There appeared to be no correlation between the rate of dark adaptation and age.

In an attempt to distinguish the proportion of different factors contributing to the ageing process, GUNKEL and GOURAS (1963) suggested that light of green or longer wavelengths should be used in the test patch. This would enable lens changes to be differentiated from other physiological ageing processes. This recommendation has been followed in modifying the dark adaptation apparatus for the present study, so that lens changes have a minimal effect on the dark adaptation curves of different age groups.

(iv) Modifications

Aims/

Aims

In setting out to modify the basic dark adaptation technique, there were several aims in mind. Firstly, a combination of stimulus factors was desirable which accentuated the transition point from cones to rods in the dark adaptational process. Secondly, the variability in dark adaptational threshold data within an individual was always large.

It was reported in the perimetry section (page 220) that the 0 - 100% frequency of seeing curve covers 0.4 log units in a trained observer whose adaptational level has reached a stable state. The dark adaptation process, which by definition is a state of continual change, requires the extraction of threshold data from a changing process in untrained observers. The resulting variability in the threshold is so large that any α point is frequently masked by the inherent variability in the measurement. A change in method was required which would reduce the variability in the threshold, improve test reliability, and accentuate the α point. Variability in the thresholds in addition to depending on the method of measurement, could also result from conditions prior to preadaptation (WOLF et al, 1960). If the visual system was not allowed to reach a stable state before standard testing procedure began, variation in the thresholds could be twice as great as would occur if a dark adaptation period/

period proceeded preadaptation. To accentuate the α point, either high intensity preadaptation and/or a violet test patch could be used. However, violet test patches are particularly sensitive to lens changes, and high preadaptation is often not desirable in clinical testing.

The third consideration arose from the fact that in situations where the thresholds were raised, it was often impossible to decide whether cones or rods were active at a particular threshold point. If a technique could be devised which gave at any moment in the dark adaptation process an indication of whether rods or cones were active at that point, the additional information would be an important contribution to the test.

Finally, the dark adaptation test was being used in a battery of tests where there was a limited time available for testing. The normal dark adaptation curve required at least twenty minutes in the dark following preadaptation. Any modifications which increased this period would be undesirable for routine testing.

With these points in mind several modifications were made to the standard dark adaptation procedure. The principle behind the method is described first, followed by the instrumental modifications towards this end./

end.

(v) The New Procedure

The method employed rests upon the following assumptions. It will be recalled that in the dark adaptation process the first part of the curve is dependent on photopic or cone response. This is followed by a transitional phase in which both cones and rods are active in the determination of visual thresholds. Finally the scotopic system or rods take over and determine the visual response down to the state where the eye is fully dark adapted.

In the early stage of dark adaptation where vision is mediated by photopic processes, the sensitivity of the eye to different wavelengths is indicated by the photopic luminosity curve. For any two wavelengths there will be a sensitivity difference characteristic of the photopic system. If therefore, following preadaptation, the sensitivity of the eye is measured to two test patches of different wavelengths, the dark adaptation curve will show a separation between the curve for each wavelength which is characteristic of cone vision and characteristic of the energy differences between the two test patch wavelengths.

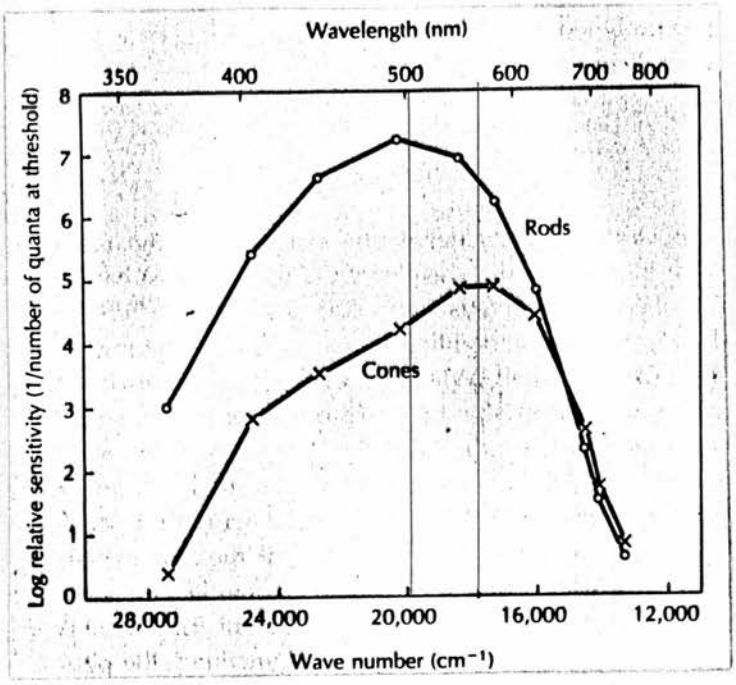
In the final stages of dark adaptation when vision is mediated by the scotopic process, it is the scotopic luminosity curve which indicates the relative sensitivity of the eye to the two wavelengths. There is now a new/

new separation between the dark adaptation curves for the two wavelengths which is characteristic of rod vision, and characteristic of the energy differences between the two test patch wavelengths. Consequently:-

1. The early separation = photopic function + energy differences
2. The late separation = scotopic function + energy differences.

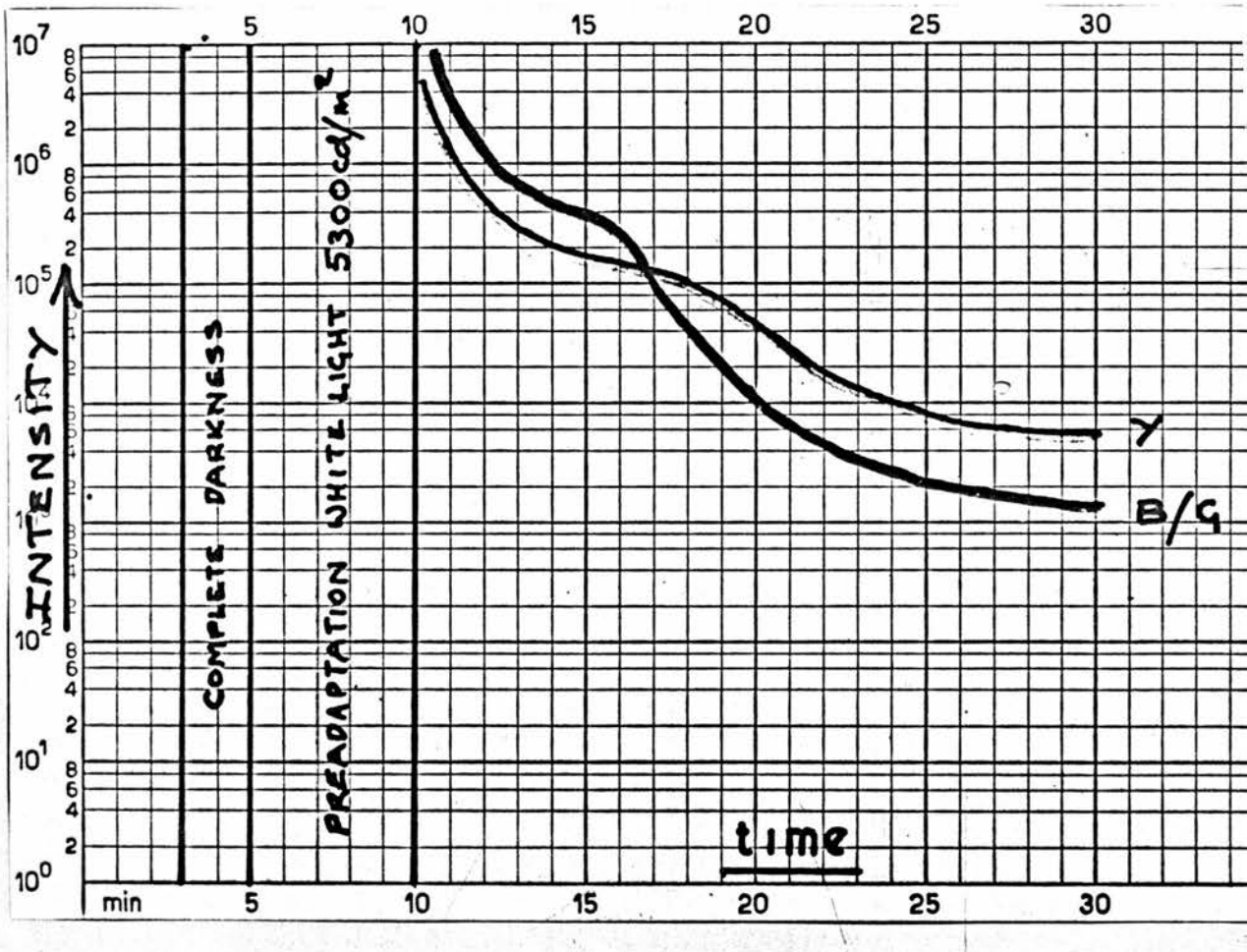
As the energy differences are constant in the measurement of either early or late dark adaptation thresholds, it is the relative separations between the curves which indicate whether it is the photopic or scotopic system which mediates vision. Therefore, by inspection of the separation between the dark adaptation curves for the two test patch wavelengths at any point in time, it is possible to determine whether cones or rods are responsible for vision at that point. In the intermediate transitional phase of dark adaptation, the separation between the curves will change from that characteristic of cones, to that characteristic of rods. At any moment in this transition the separation between the curves reflects the proportion in which rods and cones contribute to the mixed response.

It is clear that, in principle, any two wavelengths will suffice. However, it is advantageous to choose a pair in which the change between rod and cone response/



Photopic (cone) and scotopic (rod) spectral sensitivity curves. (After Wald, 1945).

Figure 90



response will be maximised. An additional restriction and refinement on the method, is the choice of a pair of wavelengths so that cone function results in the threshold for one wavelength being below the other, but rod function results in the reverse situation. Not only does this help to distinguish cone from rod function, but in addition it gives a clearly defined index of the α point, which becomes the point where the two dark adaptation curves cross. (This was an important requirement in selecting an alternative method. Using the new technique it is achieved without high intensity preadaptation, and without a short wavelength test patch).

The method is summarised in Fig. 90 . The two wavelengths which were eventually chosen for the test patches are shown in the diagram. Although the method is illustrated here for test patches consisting of monochromatic light, in principle any two coloured lights can be used. With very broad band stimuli the separations between the curves are simply reduced. Nevertheless, one separation identifies rod response and a different separation identifies cone response. (This method was utilised in Section Vb to determine the background intensity level at which a cone response is possible from the peripheral retina). The principle behind the method has been recognised in various forms by other authors. (SLOAN, 1950; ZEAVIN and WALD, 1956;/

1956; WALD, 1960; GILL, 1966). What was necessary was to adapt the method and fit it to the requirements and aims of the present study. The modifications of the equipment towards this end are now described.

Preadaptation Source

The lamps used for preadaptation in the standard instrument were replaced by two photolita No. 1 bulbs (275 w.). These are of a much higher wattage than standard instrument bulbs, and can extend the range of preadaptation intensity. The new lamps were connected to a voltage regulac control by rerouting the wiring to the adaptational source and so bypassing the built in stabiliser and transformer in the instrument. A continuous range of preadaptation intensities was now possible, and any ageing effects of the bulb could be counter-acted by increasing the applied voltage. By under running the bulbs at voltages less than 230 v. the stability of the light source was increased, and the life of the bulbs was prolonged. An adaptation intensity was chosen corresponding to a luminance of 1500ml. The voltage corresponding to this luminance was set on the regulac control and supplied from an external stabilised mains supply.

Test Patch

The question of test patch size was the first problem to consider. The instrument had to be used as a routine test procedure over a wide ranging clinical/

clinical population. In order to make its use as general as possible a centrally fixated field of 10^{o} subtense was chosen for the measurement of the dark adaptation curves. Fig. 87 indicates that with a large test field the two segments of the curve are emphasised. In addition, with a relatively large field the general function in a central area is measured, and the test is not restricted to those patients with good visual acuity. With regard to the influence of test patch size on the new method of measurement, GILL (1966) showed that there was no improvement in definition of the cross-over point with smaller test patch sizes.

A slide was constructed containing two apertures which each subtended 10^{o} when the eye was in position in the chin rest. Each aperture could be brought in turn in front of the diffusing screen of the test patch source. The variations in test patch wavelength were produced by inserting two filters of different colours in the apertures. After experimentation with a number of coloured filters the factors determining the eventual choice were:-

a.) To maximise separation differences between photopic and scotopic systems.

b.) To ensure the curves crossed over in the transition from photopic to scotopic vision.

c.) To avoid wavelengths less than 500 nm. because of lens changes with age, and macular pigment/

pigment absorptions in this region.

d.) To give a reasonable brightness when placed before the light source available in the adaptometer.

e.) To arrange one filter near 500 nm. (the diabetic group are known to have abnormal chromatic thresholds in this region, ZANEN, SZUCS and PIRART, 1957).

The eventual choice was two narrow spectral filters from the Ilford range - numbers 623 and 626. One gave a blue/green light and the other a yellow light. The dominant wavelengths of the filters are indicated by the lines in Fig. 90. The light presented to the eye was that transmitted by the filter when illuminated by a continuous source of colour temperature 2860°K.

It is an important aspect of the present technique that no photometric calibrations of the light incident on the eye are necessary. The luminance scale of the adaptometer is calibrated as a continuously varying source of white light, and it is this luminance scale which is used in the threshold measurements. This simple approach avoids photometric calibration because it is the relative luminances which are important. (Even if calibrations were carried out, they would only be appropriate for one receptor system so that the luminance scale would change as the cone/rod transitions occurred. Furthermore, in a clinical context it is most unlikely/

unlikely that luminance calibrations based upon a standard observer would be appropriate). It only remained, therefore, to balance the filter transmission with neutral filters until a cross over was ensured. A neutral filter was chosen, and placed permanently over the blue/green filter, to give a reasonable separation when either cones or rods were active in the response.

A red fixation light was placed in the centre of the 10^{o} field and run from a variable external source. (The standard fixation system could not be used because of the position of the slide containing the two coloured filters.)

Recording System

In the standard instrument, the test patch luminance at threshold is recorded on graph paper attached to a rotating drum. The experimenter controls this luminance manually by turning a knob which adjusts a neutral wedge, in front of the test patch source. The position of the knob at the threshold luminance can be transferred to the graph paper by a metal pointer which punctures a hole in the paper. This system for threshold recording has several areas where errors can arise. Because of the inherent variation in the threshold measurement, which is enhanced when the visual system is in a state of continual change as in dark adaptation, a rigorous test procedure is essential. However, if the/

the experimenter has manual control of the rate of change of the test patch luminance, an additional "experimenter variable" is introduced. A recommended procedure (MOTE, BRIGGS and MICHELS, 1954) which attempts to minimise the effect of the additional error source is the use of several practice sessions on the part of the experimenter. Nevertheless, a fully automated recording system would be advantageous in eliminating this error and in providing additional information on the threshold range, as well as the threshold position, at any point in the dark adaptational process.

An attempt was made to build an automatic recording system and so increase the accuracy of measurement. The basic component was a single phase reversible induction motor (Paravalux 50 hz 10 r.p.m.) with a capacitor 2.5 mF. incorporated for static discharge and for increase in motor efficiency. The system enabled the motor to be reversed within short intervals (i.e. two seconds). The motor was run from a 230 v. stabilised supply and had a reversible switch and a master on/off switch. Gears were attached to the motor spindle and to the adaptometer spindle connected to the neutral wedge. The instrument was arranged so that manual control of the neutral wedge was still possible if desired. The spring attached to the adaptometer arm was used to keep the gears in contact, and so ensure that the neutral wedge was connected to the motor at all/

all times.

The rotation of the sector disc presented the test patch once every two seconds. The gearing system was chosen so that the rate of change of luminance in between flashes was 0.1 log units. A pen was attached to the recording arm, to replace the metal pointer, so that a continual record of the position of the neutral wedge was transferred to the recording graph. A check was made on the motor efficiency to ensure that the number of log units of light intensity covered in any time interval was the same whether the neutral wedge was moved in or out of the light path. The way in which the automatic recording system was used is described in the following section on test procedure.

(vi) Test Procedure

The method described allows two dark adaptation curves to two different test patches to be measured following one preadaptation to white light. The single preadaptation light is important for two reasons. Firstly, it halves the time needed for testing. Secondly, the adaptational state of the eye is identical for subsequent measurements to the two test patches.

Before the test began, the procedure was explained to the subject and he was given several trials with the test patch so that he could adopt a stable criterion for responding "on or off". In order to counteract/

counteract the effects of different adaptational states in different subjects prior to the test session it was general policy to give the dark adaptation experiment as one of the last tests in the battery. Thus, each patient had been under similar room illumination for some time before the test was given. After the demonstration of test procedure the subject was seated in the dark for two minutes before the five minute preadaptation period was started. The two minutes of dark adaptation has the effect of bringing the adaptational level in each patient to the same state before testing. The motor was adjusted so that maximum light illuminated the test patch. Whilst preadaptation was taking place, the aperture was covered by a uniform white surface. The fixation light was switched on and adjusted to a relatively high intensity for the early measurements. It was subsequently reduced in intensity as dark adaptation progressed.

At the end of preadaptation the preadaptation lights were switched off and the blue/green filter was moved in front of the test patch. The subject was instructed to report the moment he was aware of the flashing light behind the fixation spot. When this was visible, the motor was switched on so that it slowly reduced the test patch brightness. At the moment the flashing disappeared the motor was reversed to increase test patch brightness. When the flashing/

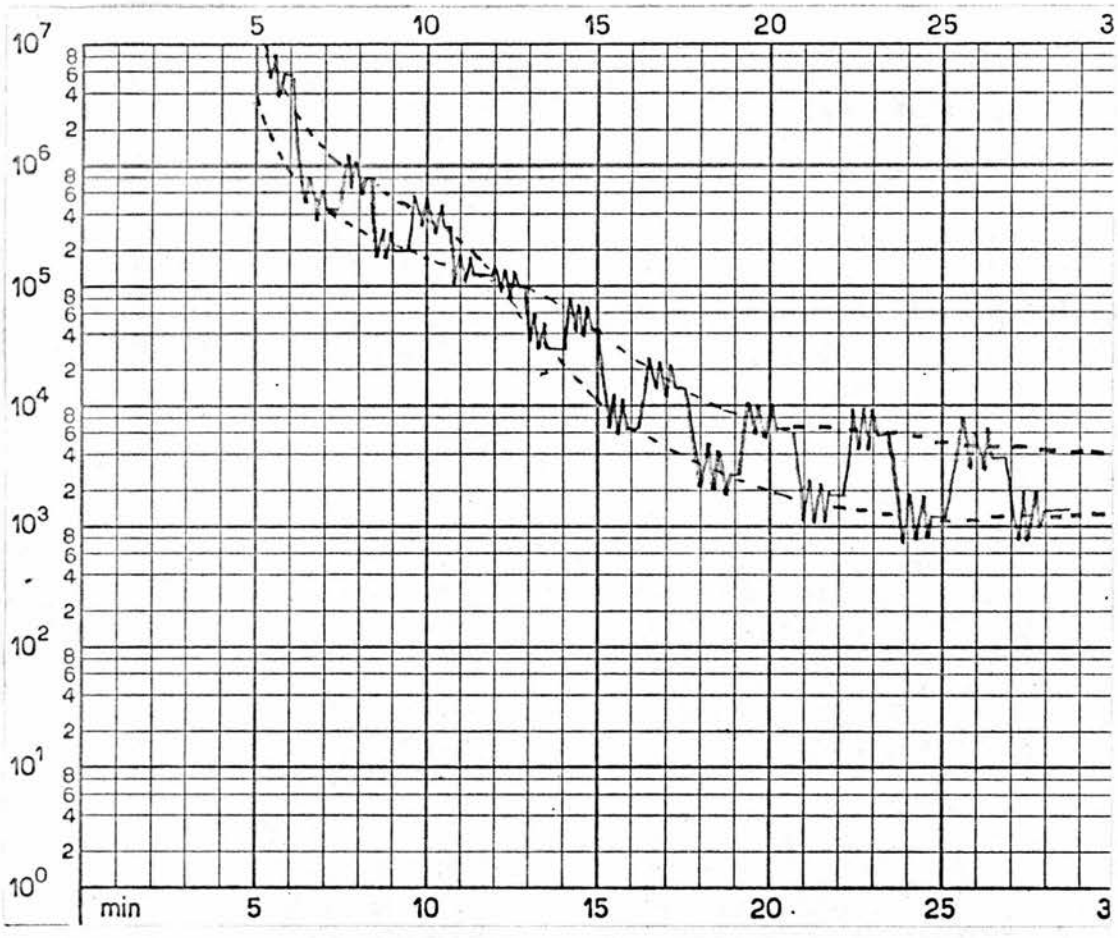


Figure 91

An illustration of the Dark Adaptation recording system.

flashing became visible the motor was reversed again. The motor was then stopped and the yellow filter introduced in the light path. The motor was then started and visibility thresholds measured in the same way to the yellow light. At the end of this measurement the motor was switched off. The subject was instructed to close his eyes and a rest of 30 seconds followed before the procedure was repeated, first to the blue/green test patch, then to the yellow test patch.

Results were obtained in this way up to the 20th minute after preadaptation. Stopping the motor between the measurements for each filter, and between pairs of measurements provided a useful means of delineating the measurements for the two filters. When the motor was stopped, a horizontal trace appeared on the recording drum. To illustrate the method a typical record is shown in Fig. 91. The method provides not only a record of the threshold values, but also an indication of the variance of the psychometric function at any point in time. One of the original reasons behind the construction of an adaptometer with a flashing stimulus was to prevent exposure to the test patch readapting the subject and thus interfering with the recovery in sensitivity following preadaptation. By instructing the subject to close his eyes between measurements, the test patch was only exposed while measurements were taken, so reducing readaptation to/

to a minimum.

The slide containing the two filters moved along a spring and had two fixed points corresponding to the correct position of each filter over the aperture. The subject responded to the presence or absence of the light by tapping on the table. When the procedure was first used, subjects handled the reversing switch themselves and so tracked their own dark adaptation curves. However, some patients found this difficult and preferred to respond by tapping. In addition there is a tendency if they are holding the switch to move it to and fro in a regular time interval irrespective of what they "see" (see Method of Average Error, page 10). Subsequent measurements were made by the experimenter controlling the reversing switch.

(vii) Norms

The data is presented in the form of log threshold on the ordinate against time on the abscissa. Such dark adaptation curves follow a curvilinear trend, which is approximately exponential. [An alternative method has occasionally been used by plotting log threshold against log time. However, RUSHTON (1963) has pointed out that spurious kinks may appear by this method, leading to false inferences regarding underlying mechanisms. An alternative way of transforming both the photopic and scotopic functions to straight lines which is recommended by Le GRAND (1968), is to plot log log/

Figure 92

Dark Adaptation Curves

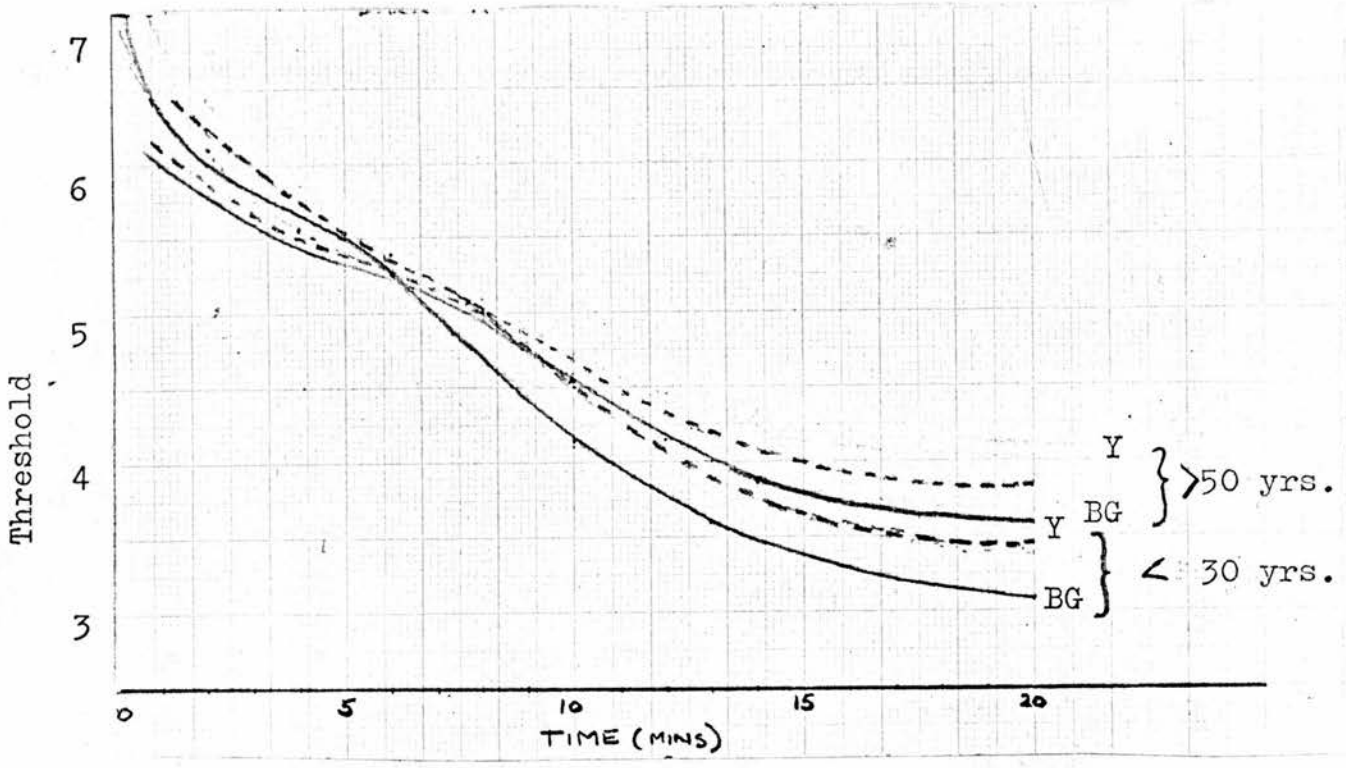
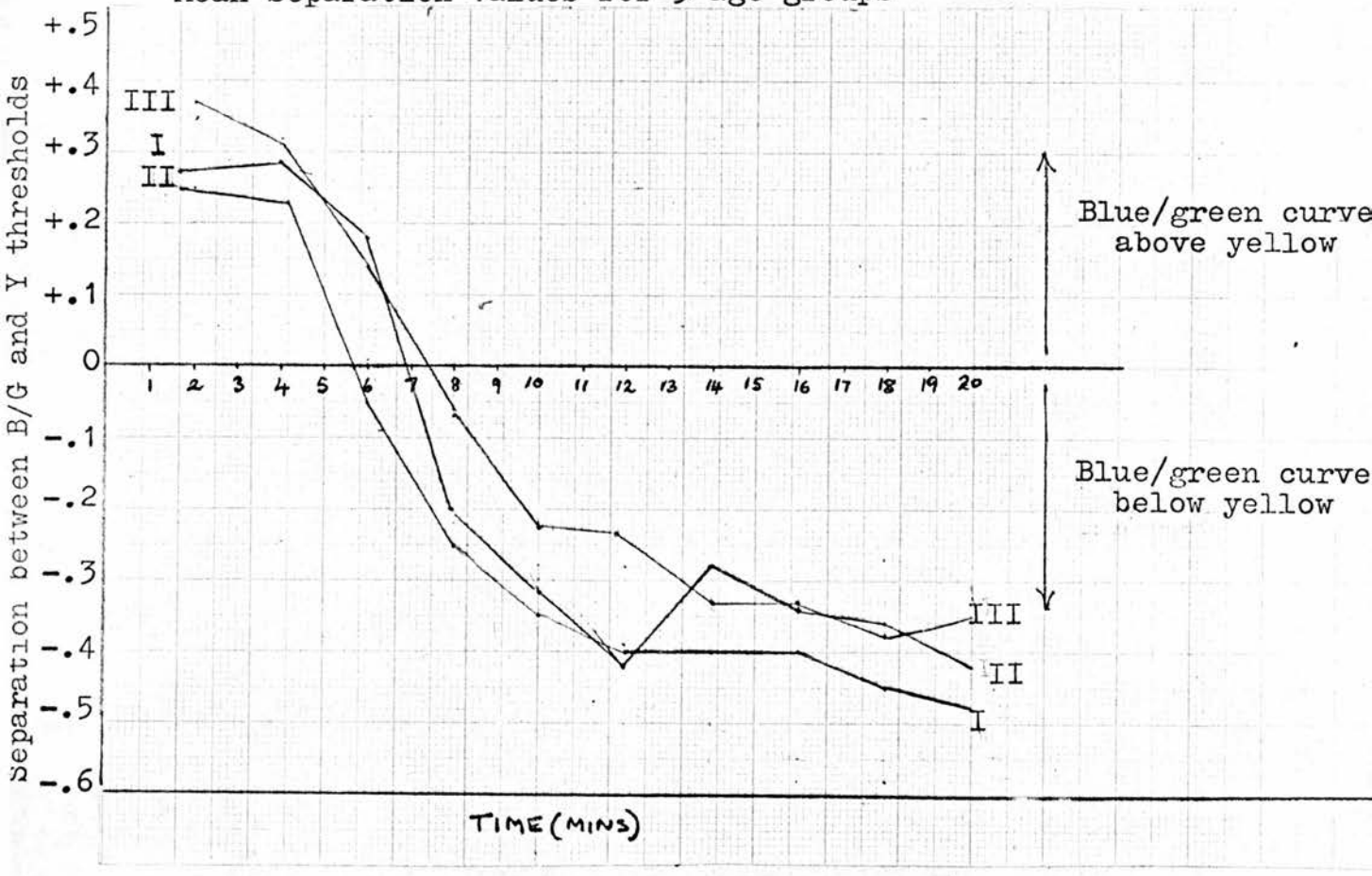


Figure 93

Mean Separation Values for 3 age groups



log luminance against time. This method was tried on the present data. In cases where the recovery rates followed an approximate exponential curve a clear indication of two distinct straight lines for each function was obtained. However, when applied to the clinical cases, in which the original data was not of this form and was almost linear when plotted in the normal way, the method was quite inappropriate.]

Using the standard method for plotting the data, the best curve was drawn through the centre of the threshold variation, so that estimates of the threshold position could be extrapolated from the curve for any time interval after preadaptation. Comparison of thresholds at fixed points along the curve enabled means and standard deviations to be calculated. As in the perimetry measurements a scale which was linear in log luminance was used for the statistics, as this corresponded approximately to a subjective scale of brightness. In addition the frequency distribution was normalised by this procedure. (An arbitrary linear scale superimposed on the log luminance scale of the standard recording graph achieved this purpose).

The mean curves for an under 30 year age group (solid line) and over 50 year old group (dotted line) are shown in Fig. 92 . The complete data for the means, and the standard deviations of threshold values at two minute intervals after preadaptation, are shown/

TABLE XVI

DARK ADAPTATION THRESHOLDS TO BLUE GREEN (B/G) AND YELLOW (Y) LIGHT

Means (M) Standard Deviations (σ) of Thresholds after t Minutes in the Dark

Age Group	Filter		t = 2	t = 4	t = 6	t = 8	t = 10	t = 12	t = 14	t = 16	t = 18	
< 30	BG	M	6.0	5.65	5.21	4.70	4.15	3.80	3.45	3.30	3.15	3
		σ	0.17	0.18	0.22	0.24	0.27	0.15	0.13	0.17	0.14	0
	Y	M	5.75	5.43	5.26	4.95	4.50	4.20	3.85	3.70	3.60	3
		σ	0.15	0.13	0.16	0.16	0.15	0.15	0.11	0.14	0.12	0
30-50	BG	M	6.08	5.69	5.25	4.78	4.20	3.83	3.50	3.36	3.25	3
		σ	0.15	0.21	0.24	0.30	0.27	0.25	0.19	0.17	0.13	0
	Y	M	5.83	5.49	5.07	4.96	4.52	4.22	3.78	3.70	3.61	3
		σ	0.18	0.12	0.17	0.22	0.28	0.19	0.14	0.11	0.15	0
> 50	BG	M	6.25	5.78	5.37	5.02	4.50	4.07	3.70	3.60	3.50	3
		σ	0.23	0.27	0.24	0.31	0.28	0.23	0.25	0.22	0.21	0
	Y	M	5.90	5.47	5.23	5.07	4.72	4.30	4.03	3.93	3.88	3
		σ	0.25	0.21	0.26	0.26	0.24	0.20	0.14	0.15	0.09	0

CHARACTERISTIC SEPARATIONS AND CROSS-OVER TIMES

Age	cones		rods		cross-over times	
	mean	σ	mean	σ	mean	σ
< 30	0.22	0.03	0.48	0.02	5.7	0.09
30-50	0.20	0.03	0.43	0.05	6.3	1.1
> 50	0.35	0.06	0.36	0.04	7.6	1.1

shown in Table XVI for three age groups. For the youngest age group the mean dark adaptation curves show the expected change with time. The characteristic separation for cones is equal to 0.25 log units; the characteristic separation for rods is equal to 0.48 log units; and the cross over point occurs at 6 minutes. It is important to note that in every individual case in this normal group there was always a point at which thresholds for blue/green were above yellow, and always a later point at which the thresholds were reversed. In order to establish that two distinct curves were present a correlated 't' test was carried out on the youngest age group between the yellow thresholds and the blue thresholds at 4 minutes (t_{4m}) and at 12 minutes (t_{12m}). Both values were significant beyond the .01 level (t_{4m}= 4.3: t_{12m}= 6.5). Within this group, correlations between the blue/green and the yellow thresholds at 4 and at 20 minutes were both highly significant (r = .54: r = .66) respectively.

The effect of age can be seen from Fig. 92 in which the threshold values are plotted for the youngest and oldest age group. The general age effect is a raising of both curves by about 0.4 log units in the rod section and by approximately 0.20 log units in the cone section. The differences in the cone thresholds are not significant but those for the rod thresholds are significant (t = 1.2 cones; t = 3.7 rods). It appears/

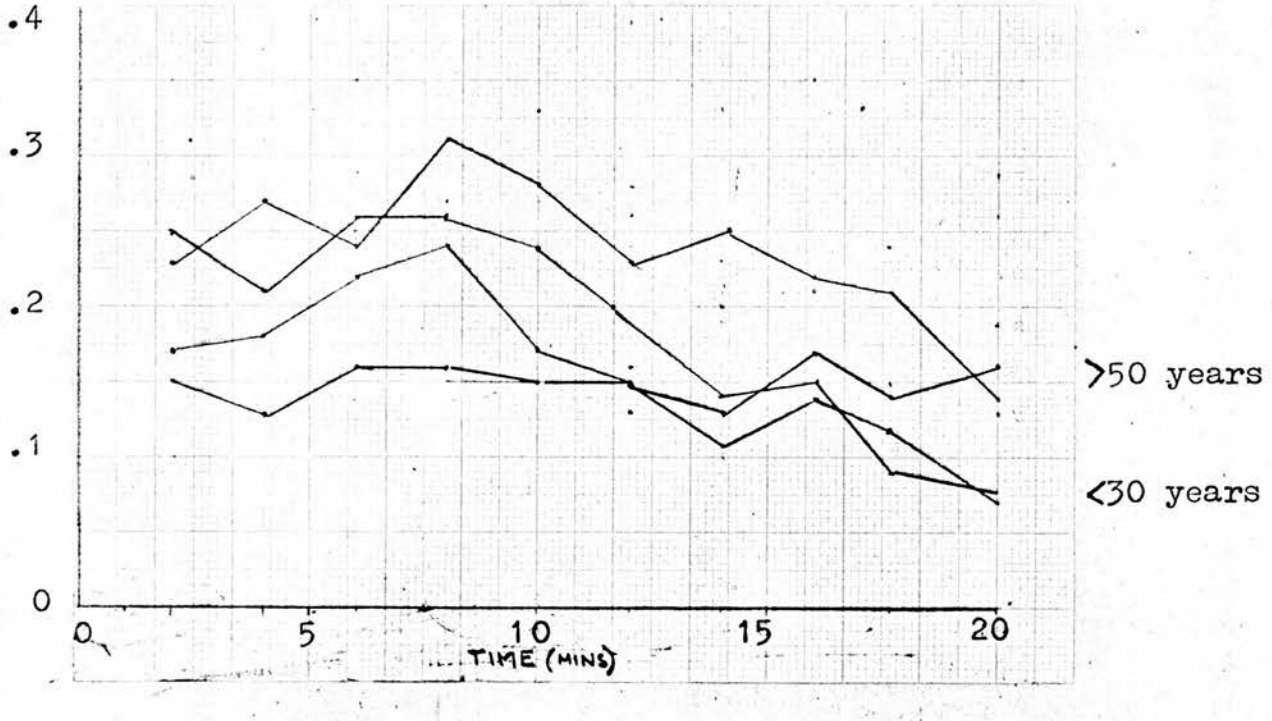
appears from Fig. 92 that the characteristic separation between the curves changes with age for both cones and rods. Means and variations in these separations are given in Table XVI for the three age groups. This is shown more clearly in Fig. 93 in which the difference (log. threshold blue/green - log threshold yellow) is plotted on the ordinate against different time intervals on the abscissa. In the early part of dark adaptation, when the blue/green curve lies above the yellow curve, the threshold intensity for blue/green is greater than that for yellow. Consequently, the difference is positive, and the separation lies above the horizontal line. For values at which the blue/green curve lies below the yellow, the differences are negative and lie below the horizontal line. The transition point is given by the intersection of the curves with the horizontal line. The effect of age is:-

1. to make the initial cone separation greater
2. to make the rod separation smaller
3. to delay the point at which the curves cross

There is one very simple hypothesis which accounts for these three findings, namely, that the blue/green threshold is raised with age more than the yellow threshold. This hypothesis would be in keeping with general age changes discussed in Section IVb, which show a greater loss with age at shorter wavelengths. Fig. 92 shows that both the yellow and blue/green/

Figure 94

Variability in thresholds at different times after preadaptation.



green thresholds have been raised. However, if the blue/green shift is greater than the yellow shift in the early stages of dark adaptation, a greater separation between the curves will occur. Similarly, in the later stages of adaptation, the greater shift in the blue/green curve with age now takes the curve closer to the yellow one, resulting in a smaller separation between them. As the whole of the blue/green curve is moved higher along the ordinate parallel to the abscissa, the curve must cut the horizontal at a later stage. The correlation between age and the cross over point was significant ($r = .39$ $p < .01$), indicating that the mean cross over times illustrated in Fig. 93 represented a genuine age shift.

The mean values of cross over time for each age group is shown in Table XVI, together with an indication of the likely variation in cross over to be expected in the three age groups. A comparison of the standard deviations at the youngest and oldest ages are given in Fig. 94 (taken from Table XVI). The standard deviations are highest around the 8th to 10th minute after preadaptation, and tend to have their lower values at the 20th minute. This may be explained by the fact that the rate of change of sensitivity is probably greatest at the 10th minute where the rod function has just taken over, and probably least at the 20th minute after preadaptation. (The rate of change of sensitivity/

sensitivity is almost certainly greatest immediately following preadaptation. However, the earliest recorded measurement for the analysis was at 2 minutes and so the record does not show the very earliest changes).

The variation in threshold measurements is likely to be greatest where the visual system is most unstable, and likely to be least when the visual system is in a stable condition. Consideration of the rate of change of sensitivity against time (i.e. the gradient of the curves in Fig. 92) indicates that this is greatest in those regions where the standard deviations are greatest. It is interesting to compare these standard deviations with those obtained under stable adaptational conditions in increment threshold measurements, (Fig. 77). The fact that they are comparable and that the standard deviations in dark adaptation tend to be smaller than those reported by GILL, 1966 (F ratio = 2.47 $p < .05$) is an indication that the new method of recording the data reduces the variability in the measurement to a level of accuracy reached in perimetry.

The average intra individual variation, as given by the range of intensities at each threshold point between one reversal of the motor and the next, was found to be 0.3 log units.

In summary, norms have been established for the following variables in dark adaptation testing:-

1. The absolute level of the "blue/green" thresholds/

thresholds at any time up to the 20th minute following preadaptation.

2. The absolute level of the "yellow" thresholds at any time up to the 20th minute following preadaptation.
3. Age variations in blue/green and yellow thresholds.
4. Characteristic separations between blue/green and yellow thresholds in both rod and cone vision.
5. Variations in this separation due to age.
6. Variations in transition times between rod and cone vision.

VI PROCEDURE AND RESULTS

Introduction

Studies on several different clinical groups are reported in this section. In some cases it was difficult to decide whether to treat any group as a whole and use available statistical methods, or whether to report individual cases within the group. The general procedure was to use group analysis in any group which could be considered to be homogeneous with respect to the clinical diagnosis, that is a group which contained individuals with the same condition and differing only in degree. On the other hand, if there was strong evidence that individuals had distinctive characteristics, then the individual cases were presented.

Three of the groups were deliberately planned as separate studies and a fourth group was made up of miscellaneous conditions. The third and fourth groups consisted of patients referred to the retinal function unit in the hospital. In these latter groups, in addition to psychophysical tests a clinical examination, fluorescein angiography and electrodiagnostic tests were given as part of the routine testing with the aim of cross correlating information from these different sources.

Because relatively little data is available under strictly controlled experimental conditions, an attempt/

attempt has been made to use as many tests in the battery as possible. However, there were obvious practical difficulties. Each test lasted approximately twenty five minutes, and consequently more than one appointment was necessary to obtain an overall picture of visual function. Several appointments were needed in the case of patients attending the retinal function unit, thus making considerable demands on each patient. If time was limited, tests were selected which were thought to give the most valuable information.

Another practical limitation on the tests was the patient's visual acuity. In cases of deteriorated vision when Snellen acuity was already affected, it was often impossible to give some of the finer macular tests. The Helmholtz colourimeter was particularly limited in this respect. A telescopic viewing system was found to be a very difficult task with even slightly reduced acuity. However, one of the justifications for sophisticated tests is that they may detect early visual losses while general vision remains good. Consequently an attempt was made to give particular attention to those groups likely to have good vision. Nevertheless, several patients with reduced vision were tested. In some cases this simply confirmed a known loss of function. In others, the nature of the loss (e.g. whether predominatly red/green or yellow/blue) was investigated for diagnostic purposes so that the degree/

degree of severity of each type was known. Each group will be treated as a separate entity. A brief account of any previous results will be followed by an analysis of the present data.

a.) DIABETES

Background

An acquired dyschromatopsia of the yellow/blue axis was reported in diabetes by LEBER (1916). However, it is studies of the later period (beginning around 1950) which will be reported, as diabetes has only satisfactorily been controlled during the last 40 years.

ZANEN (1953) described the colour vision of three diabetics. All these showed a loss of sensitivity to blue, but in addition one patient showed losses to yellow, and another losses to red and green. A subsequent study by ZANEN, SZUCS and PIRART (1957) showed diabetics to be different from normals, and to have noticeable losses in the blues and greens (particularly around 496 nm.) and slight losses in the reds (around 698 nm.). Of the eleven subjects tested, the five 'thin' diabetics were worse than the six 'obese' ones. These results are typical of the general findings on diabetic colour vision. Yellow/blue defects have been noted by DUBOIS-POULSEN and COCHET,(1954); FRANCOIS and VERRIEST (1957) COX, (1961); VERRIEST (1964); and concomitant red/green losses by HONG (1957); and VERRIEST (1964). DUBOIS-

DUBOIS-POULSEN and COCHET (1954) and FRANCOIS and VERRIEST, (1957), found yellow/blue defects in patients with no apparent retinopathy. COX (1961) examined five patients all of whom had yellow/blue defects. The defects resembled congenital tritanopia and tetartanopia with additional losses in the photopic luminosity function at short wavelengths. Again VERRIEST (1964) examined twenty patients and found colour defects either with no apparent axis or with a yellow/blue axis. The latter was more pronounced resembling a tritanopic axis, with only slight concomitant defects in red/green discrimination. In cases where red/green defects did exist, the mid-matching point was most frequently shifted to the red and the photopic luminosity curve was normal. HONG (1957) reported a similar shift towards the red but a displacement of the photopic luminosity function towards the short wavelengths. These defects were present in cases with normal visual acuity and no apparent retinopathy. Finally, ZANEN (1959) reported that one diabetic had abnormal achromatic (detection) thresholds at all wavelengths but normal photochromatic intervals (i.e. the difference between the detection and the recognition thresholds).

It was apparent that none of these studies involved more than twenty eyes and that there were often additional clinical factors complicating the data. Furthermore, ageing changes in normal vision were not/

not available until LAKOWSKI (1958, 1962), VERRIEST, (1963), and RUDDOCK (1965) demonstrated that the age effect was influencing the same spectral region where former studies showed diabetics to have losses.

In an attempt to counter these factors, KINNEAR (1965) carried out a comprehensive study on a diabetic population of over 500 patients. Control groups were established for age variations and care was taken to isolate the variables of acuity, duration of diabetes, and retinal state. The Ishihara Plates, Farnsworth Munsell 100 hue test, and Pickford Nicholson anomaloscope formed the test battery. In a group of 387 diabetics of whom 76% had ophthalmoscopically normal fundi and $<1\%$ corrected reading acuity $<$N12, 30% were found to have reduced colour vision. Seventy per cent of the diabetics had colour vision results which fell within the limits of normal population. In the 30% with reduced colour vision the yellow/blue and blue/green equations were found to be most affected while only 5% of this group had concomitant red/green losses beyond normal limits.

Kinnear reported that a striking feature of this data was the inability to predict the level of colour vision from the duration of diabetes or the degree of control of the blood sugar level. The only significant (but weak) relationship existed between duration and the matching ranges on the blue/green equation. The/

The other colour vision tests showed no relationship with duration. However, correlations did exist between the colour vision test and retinal state, the colour results being poorer as the retinal state deteriorated. Patients with haemorrhagic retinopathy exhibited the worst colour losses although maintaining reasonable black and white acuity. Kinnear found that 75% of the diabetics showed an improvement in colour vision if the field of view was enlarged (from $1\frac{1}{2}^{o}$ to 3^{o}). Thus in the early stages of diabetes normal blue vision can be restored by increasing the field of view, suggesting facilitation in the neuronal elements, and conversely suggesting that colour vision tests are sensitive indices of neuronal degeneration.

Present Studies

This is in two parts.

1. Transformation and Follow-up Study:-

The transformation described in Section Va was performed on Kinnear's raw data. The purpose of this was to enable direct comparisons between red/green, yellow/blue and blue/green discrimination by placing them all on a common uniform chromaticity scale. A follow-up study on the retinal state was carried out as over five years had elapsed from the date on which the initial results were collected. Of particular interest was the subgroup of diabetics who had no visible retinopathy in 1965. The question asked was whether the/

TABLE XVII

AGE	NUMBER TOTAL	M	F	% ACUITY N5	% DURATION >4 YEARS	% ONSET >14 YEARS
< 20	58	35	23	95	31	24
20 – 29	100	57	43	96	69	51
30 – 39	107	70	37	92	77	89
40 – 49	142	59	83	81	73	94
50 +	142	51	91	64	84	100
TOTAL	549	272	277	83	71	79

Quantitative summary of diabetic population

TABLE XVIII

AGE	N	INCIDENCE of CATEGORY 2 few ma's %	3 many ma's %	4 worse %	NAD %
< 20	58	2	0	0	98
20 – 29	100	17	3	4	76
30 – 39	107	23	4	1	72
40 – 49	142	15	11	3	72
50 +	142	12	22	7	59
TOTAL	549	15	10	3	72

Categories of retinopathy

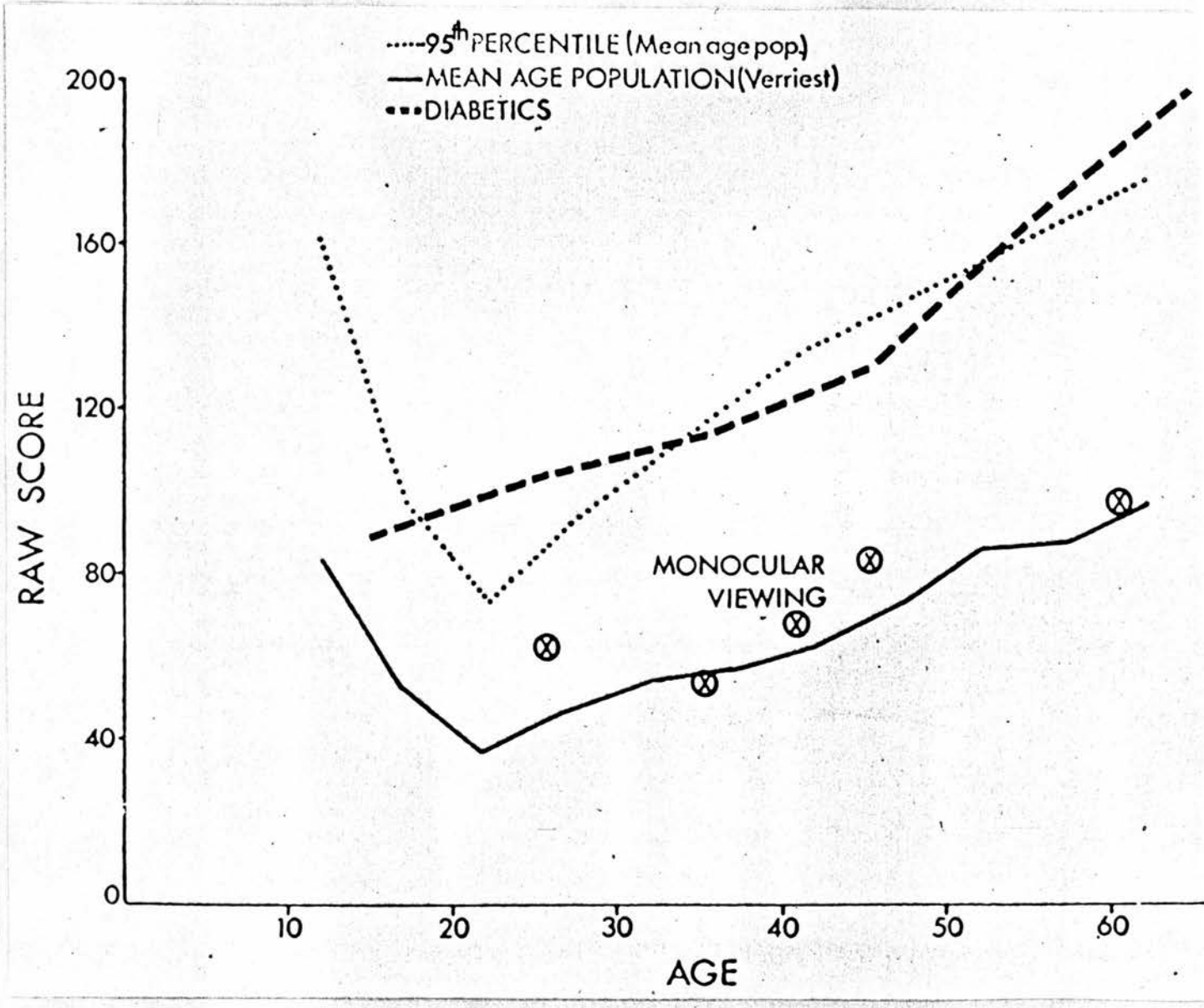

.....95th PERCENTILE (Mean age pop.)
—MEAN AGE POPULATION (Verriest)
•••DIABETICS
200
160
120
80
40
0
RAW SCORE
MONOCULAR
VIEWING
10
20
30
40
50
60
AGE

Figure 95

the diabetics in this subgroup who had the greatest colour vision losses in 1965 were the ones who had subsequently developed retinopathy. The relationship between change in retinal state and colour vision was investigated for diabetics in other subgroups.

2. Comprehensive Analysis of Macular and General Function:-

A comprehensive analysis of visual function was performed on a group of young diabetics who had good visual acuity and no visible signs of retinopathy. A factor analytic procedure was used to examine the inter-relationships in the data.

1. Transformation and Follow-up Study *

(i) Transformation Data

A Comparison of Diabetics with Normals

Kinnear's population is given in detail in Table XVII Most patients had normal acuity, and the sex distribution was equal except in the group of older diabetics. A comparison of the diabetic group as a whole with the normal population studies, showed interesting differences on the Farnsworth Munsell 100 hue test and the Pickford anomaloscope. (No statistically significant differences were shown on the Ishihara plates).

Fig. 95 shows the 100 hue scores. The binocular mean of Verriest's data is comparable with the monocular mean of Kinnear's study. The diabetic mean runs close/

* Part of this data was presented in a paper 'Colour Vision and Diabetes' by LAKOWSKI, ASPINALL and KINNEAR to the Ophthalmological Society of the United Kingdom, 1972.

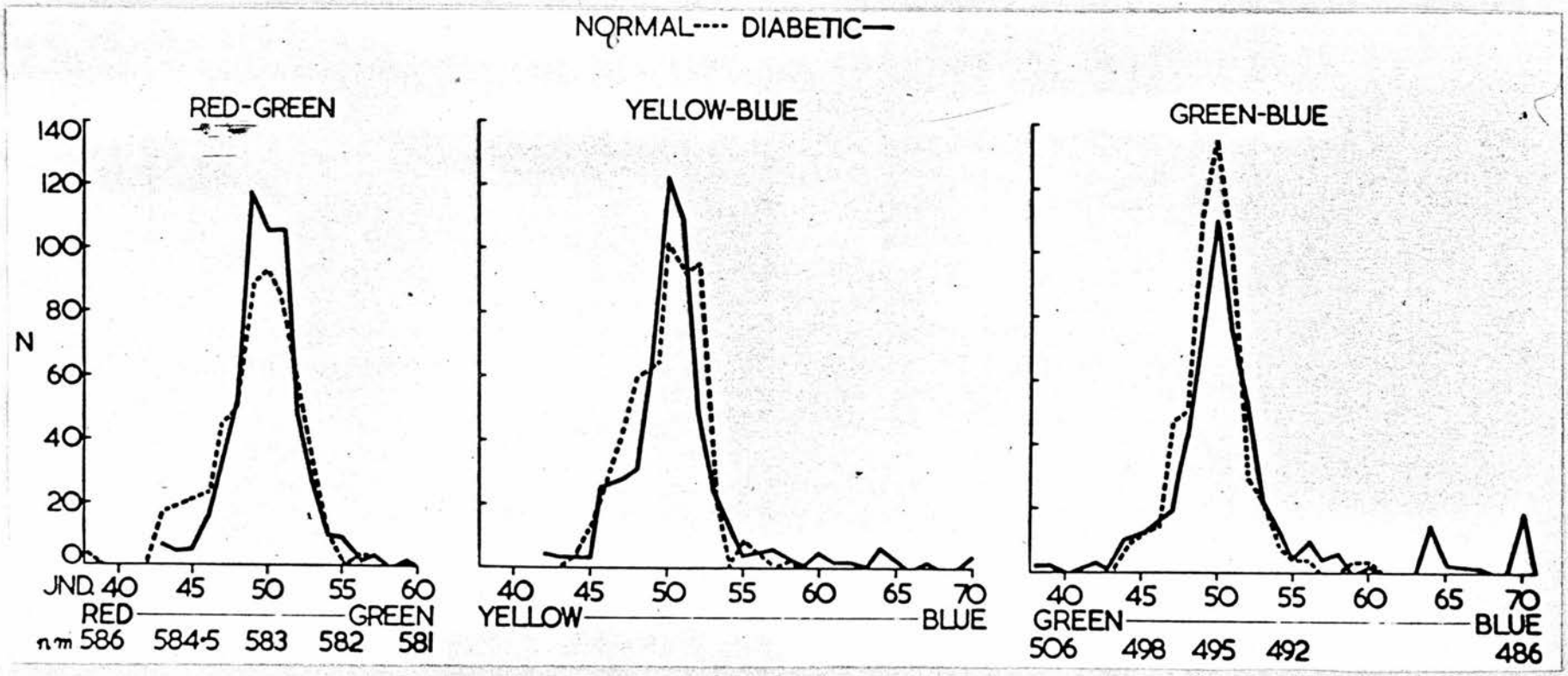

NORMAL---- DIABETIC—
RED-GREEN
YELLOW-BLUE
GREEN-BLUE
N
140
120
100
80
60
40
20
0
JND. 40 45 50 55 60
RED GREEN
nm 586 584·5 583 582 581
40 45 50 55 60 65 70
YELLOW BLUE
40 45 50 55 60 65 70
GREEN BLUE
506 498 495 492 486

Figure 96

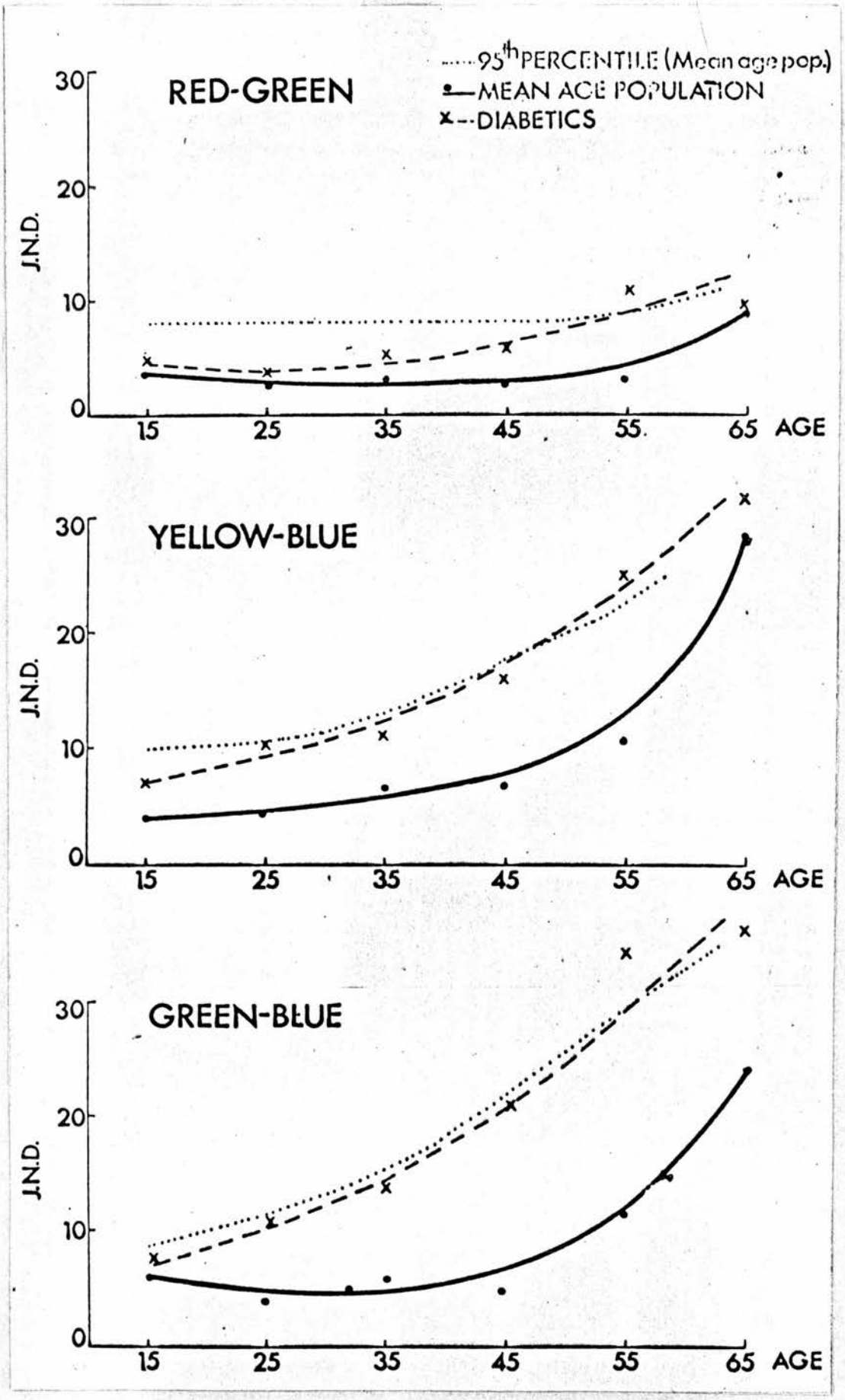

95th PERCENTILE (Mean age pop.)
MEAN AGE POPULATION
DIABETICS
RED-GREEN
YELLOW-BLUE
GREEN-BLUE
J.N.D.
AGE
0
10
20
30
15
25
35
45
55
65

Figure 97

close to the 95th percentile scores of the normal population, and the two populations differ significantly on this test. Fig.96 and 97 show the comparison of the two groups on the Pickford anomaloscope. In Fig. 96 the mid-matching points of the two populations do not differ, although there are some individuals on the yellow/blue and blue/green equations who have anomalous mixture ratios. (The abscissa is in j.n.d.'s with arbitrary mid-matching point of 50 as described in Section Va). In Fig.97 the matching ranges are compared. Here the significant differences are in the yellow/blue and blue/green equations with the mean of the diabetic group again lying close to the 95th percentile line for the normal population. The difference in mean scores for normals and diabetics in the red/green equation is not significant, except in the oldest age group. These results show that in diabetes it is principally the discrimination of the yellow/blues and blue/greens which is affected. The similarity of mixture ratios in diabetics and normals shows that the receptor system of diabetics is essentially the same as that of normals.

Comparisons within the Diabetic sample

If the diabetic group is now divided in terms of retinal state, the distribution within the diabetic sample is shown in Table XVIII.

The category N.A.D. refers to those diabetics with no visible retinopathy (nothing abnormally different)./

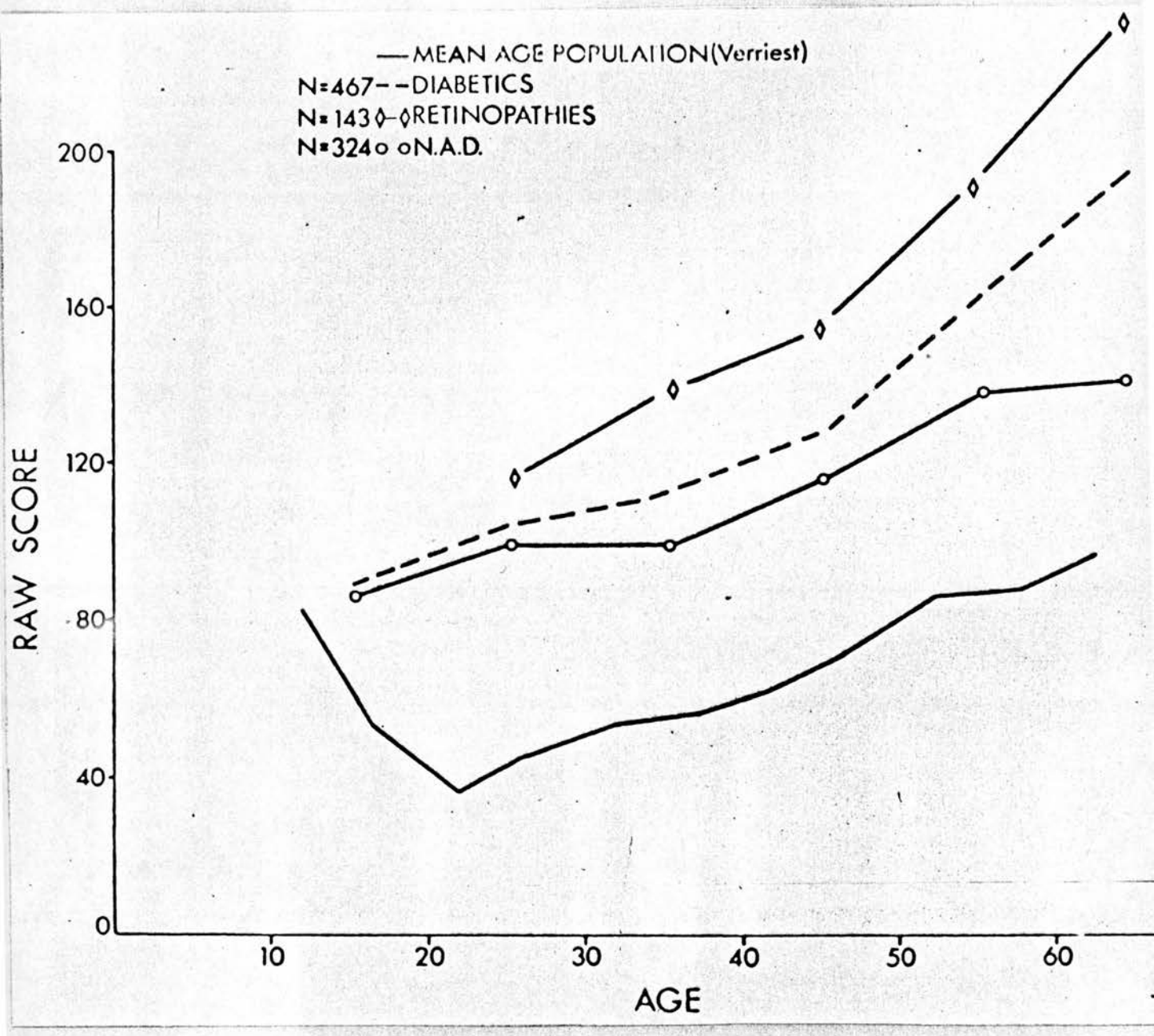

—MEAN AGE POPULATION(Verriest)
N=467--DIABETICS
N=143◊-◊RETINOPATHIES
N=324o oN.A.D.
200
160
120
80
40
0
RAW SCORE
10
20
30
40
50
60
AGE

Figure 98

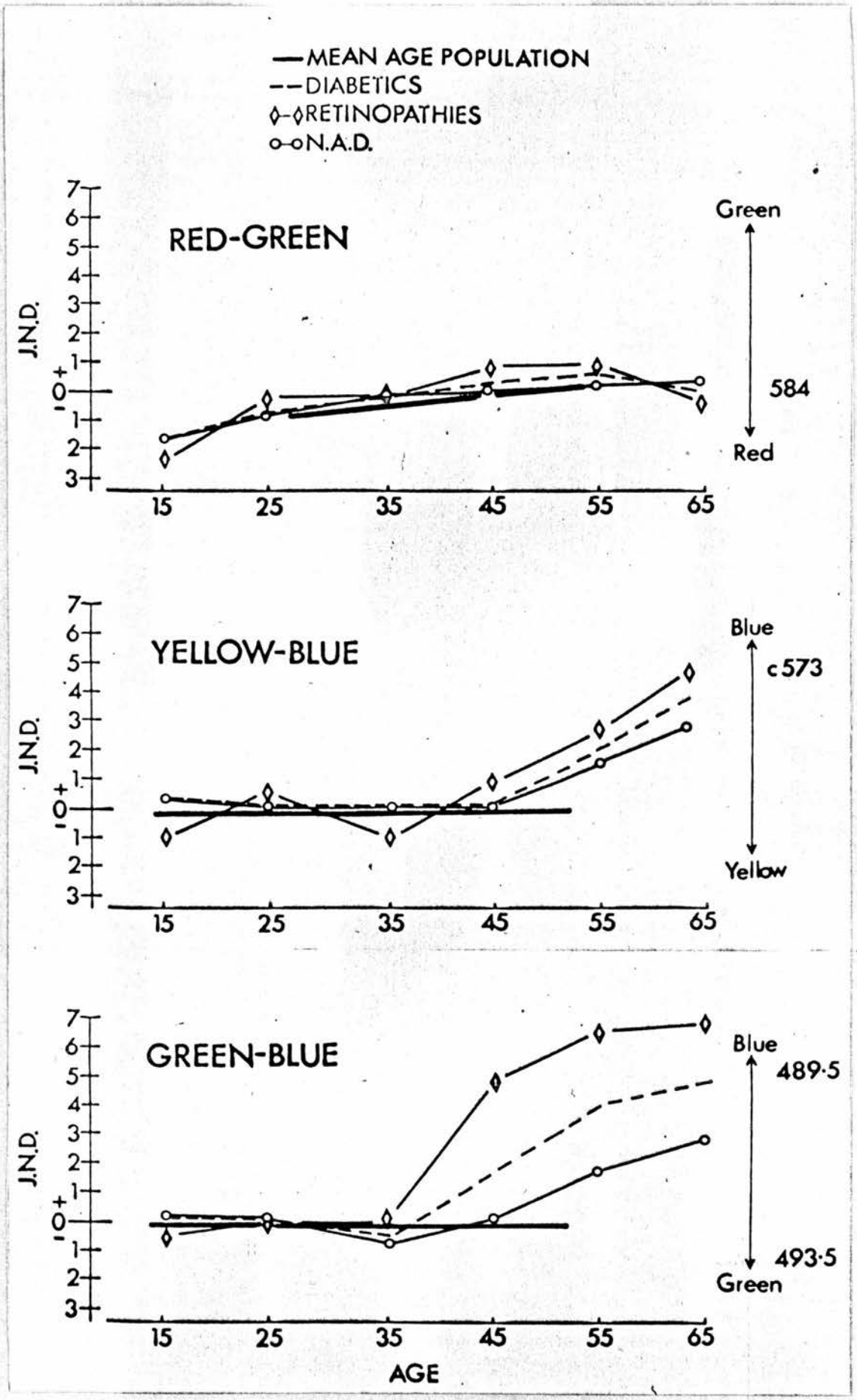

—MEAN AGE POPULATION
– –DIABETICS
◊–◊RETINOPATHIES
o–oN.A.D.
RED-GREEN
J.N.D.
Green
584
Red
YELLOW-BLUE
Blue
c573
Yellow
GREEN-BLUE
Blue
489·5
493·5
Green
15
25
35
45
55
65
AGE

Figure 99

different).

Category 2 refers to the presence of a few scattered microaneurisms;

Category 3 to the presence of many microaneurisms plus occasional blot haemorrhages and hard exudates;

Category 4 to the presence of more serious changes (soft exudates, flame haemorrhages and secondary proliferative changes).

The resulting colour vision scores of two subgroups of the diabetic population i.e. those without retinopathy (N.A.D.'s) and those with retinopathy (Categories 2, 3 and 4) are given in Figs.98,99,100. Fig. 98 shows that the 100 hue scores of those diabetics with retinopathy is higher than those diabetics with normal fundi. The diabetics with normal fundi are still considerably worse on this test than those normals of comparable ages. The differences between retinopathy and the N.A.D. groups; and the N.A.D. and normal groups are significant after the age of 30 years (Chi square test).

Fig. 99 shows the variability of the anomaloscope mid-matching points. Here the reference norms for each age group are presented as a horizontal line, with the 0 j.n.d. point corresponding to the normal mixture ratio (i.e. the 50 j.n.d. point on the arbitrary scale). Deviations in the mixture ratio are now in j.n.d.'s and the limits in the normal population extend to $\pm$ 3 j.n.d.'s. The red/green equation shows that there are no shifts/

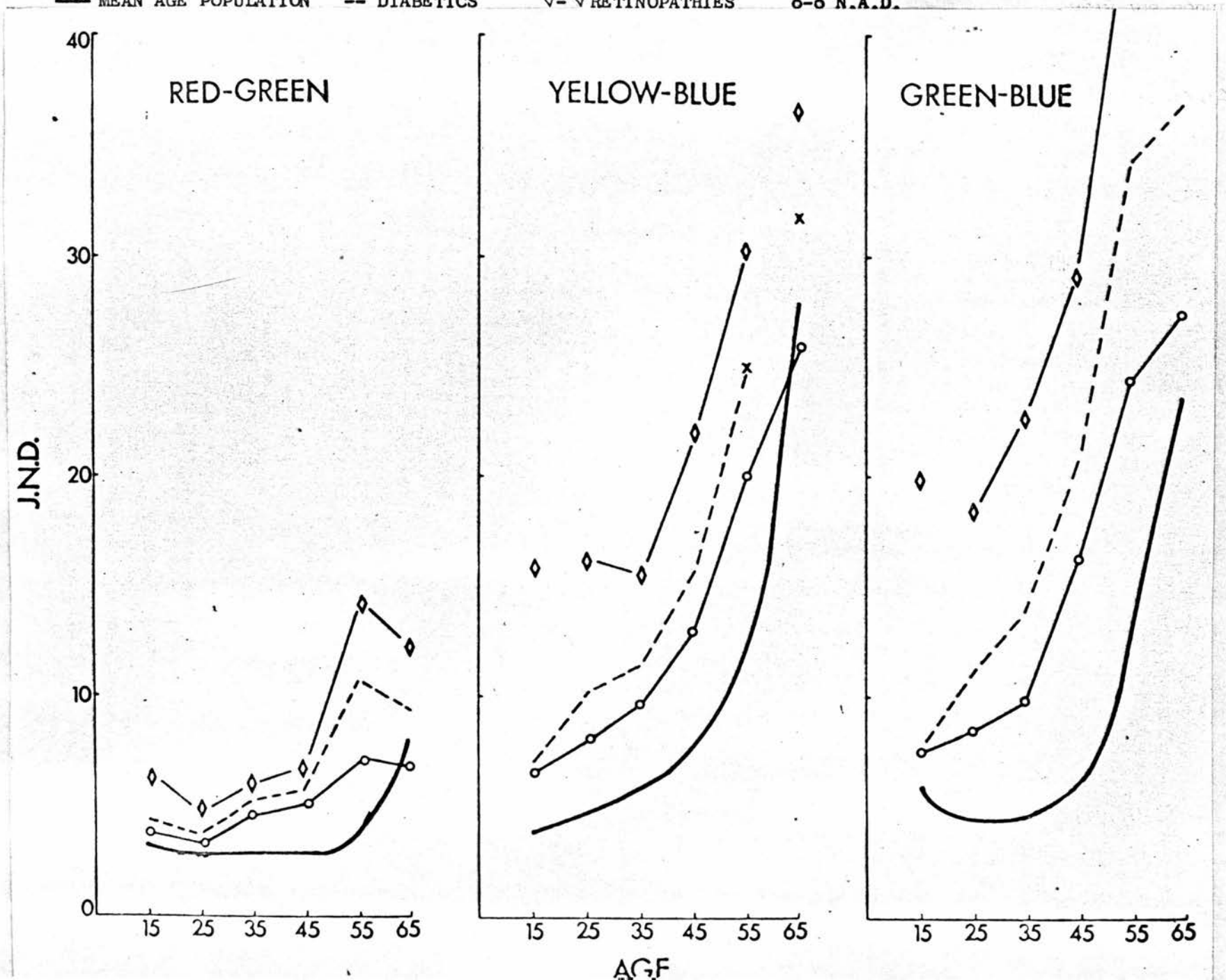

—— MEAN AGE POPULATION -- DIABETICS ◊-◊ RETINOPATHIES o-o N.A.D.
RED-GREEN
YELLOW-BLUE
GREEN-BLUE
J.N.D.
40
30
20
10
0
15 25 35 45 55 65
AGE

Figure 100

shifts in the mixture ratio whether there are retinopathies or not. On the other hand the yellow/blue equation shows a significant trend after 45 years, and the blue/green equation a significant trend after 35 years. These shifts are greatest in those diabetics with retinopathy. On both equations the shift is towards the blue end of the spectrum. Thus although diabetics as a whole show little variation from the normal population, the breakdown into separate ages and retinal categories shows that it is the older diabetics who have significant shifts in mid-matching point,and that those with retinopathy are particularly affected.

Fig.100 shows that the discrimination ranges are markedly affected on the yellow/blue and blue/green equations with the retinopathy group always worse than the N.A.D. group. In addition the scores of the retinopathy group are outside the normal limits on the red/green equation. It is also apparent that the blue/green equation gives the greatest separation between normals, N.A.D.'s, and retinopathy groups. This comparison is valid because of the uniform nature of the single scale underlying all these equations.

Discussion

The results showed that diabetics as a whole were poorer than the general population in discriminating yellow/blues and blue/greens, and that the mixture ratio was shifted towards the short wavelengths in/

in elderly diabetics who also had additional red/green losses. The colour vision losses in patients with retinopathy were greater than in those patients without retinopathy, and the greatest difference between the two groups was again on the yellow/blue and blue/green equations.

Attempts to predict the losses from clinical variables proved impossible. Some poorly controlled diabetics had good colour discrimination while some well controlled diabetics had poor discrimination. Several diabetics with normal fundi had poorer colour discrimination than those with retinopathies.

Thus there were several individual exceptions to the reported trends. However, just as in Kinnear's original data, a significant relationship did appear between duration of diabetes and blue/green discrimination at all ages, the poorer vision being associated with the longer durations. There was also a relationship between duration and retinal state so that the longer durations were associated with pathological conditions.

It appeared, therefore, that there were very complex relationships between the clinical and the colour vision variables. In an attempt to clarify these underlying relationships, Lakowski (referenced under LAKOWSKI, ASPINALL, KINNEAR, 1972) carried out a discriminant functions analysis. This was an attempt to predict the clinical category to which a diabetic/

diabetic belonged (i.e. either category N.A.D., 2, 3, or 4) given evidence of acuity, duration of diabetes, and colour vision results. (While this would appear an odd procedure to a clinician who would obviously, in practice, look at the fundus for classification purposes, it does enable the basic relationships between the variables to be investigated).

The results of the analysis were in terms of probabilities representing the likelihood of an individual belonging to any of the retinal state categories. The best prediction of retinal category was found to come from a combination of all the colour vision variables and duration of diabetes. No other available clinical variables including Snellen acuity improved the prediction, if added to this battery, or even approached this prediction level when used in isolation. It appeared, therefore, that the colour vision variables were closely related to, and were likely to reflect, the state of the retina. In addition when the duration variable was added to the colour vision variables additional information was given about the likely retinal state of a diabetic.

(ii) Follow-up Study

From the practical viewpoint the usefulness of the colour vision variables came from the follow-up study, in which the original diabetic group had their fundi re-examined. The group of greatest interest was the/

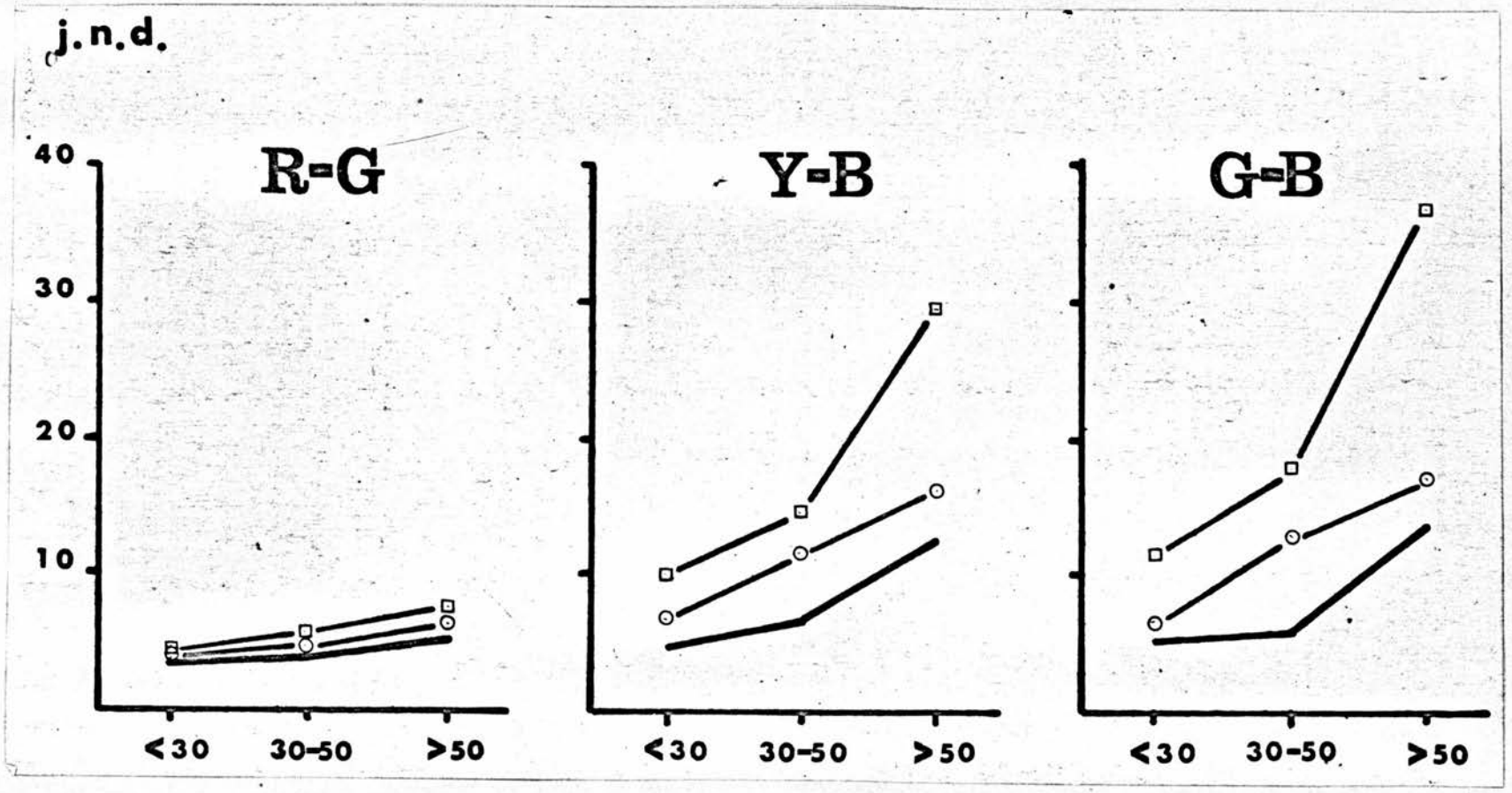


Figure 101

the group with no fundus abnormality in 1965. As many as possible of the diabetics in the group were re-checked using the system of classification described on page 291. The rechecking was done by observers who had no knowledge of the colour vision data. This is important in a classification system which has such a large subjective component. In the following discussion the change group refers to those individuals whose fundus was now classified as Category 2 or higher. The 'no change' group refers to those diabetics whose fundus was still apparently normal (i.e. N.A.D.). Because of the close association described in the discriminant functions analysis between the colour vision tests, the duration, and the retinal state, it seemed reasonable to include the duration variable together with the colour vision variables to attempt to predict the diabetics who were likely to change over a five year period.

Results

As a preliminary, the diabetics were grouped into three age groups and the results of the means of the 'change' subgroup were compared with the means of the 'no change' subgroup for the three anomaloscope equations, the 100 hue test, and duration of diabetes.

In Figs. 101 and 102, the heavy line represents the mean age scores at the three age levels. The circles represent those diabetics showing no change in their/

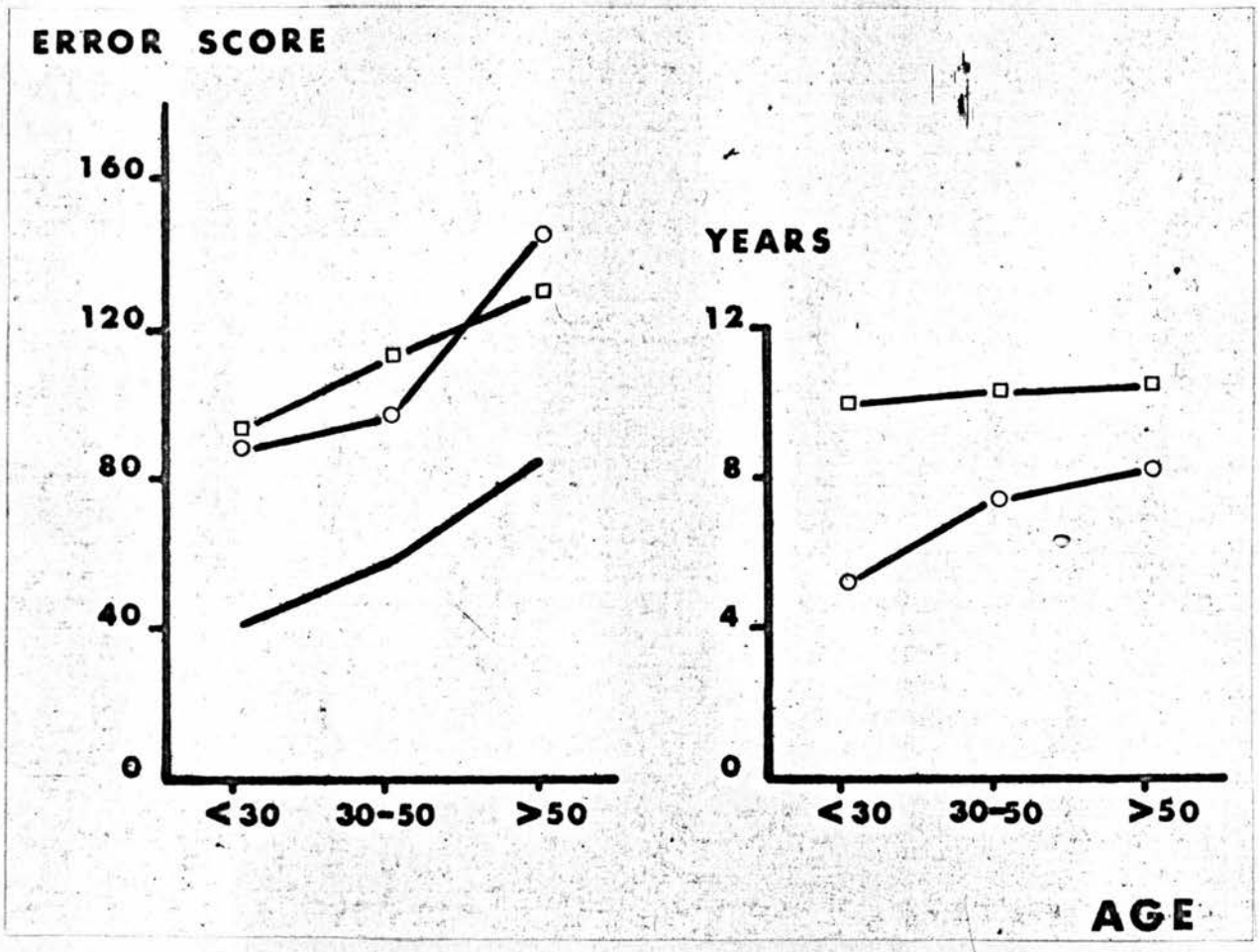

ERROR SCORE
160
120
80
40
0
<30
30-50
>50
YEARS
12
8
4
0
<30
30-50
>50
AGE

Figure 102

their fundi five years after testing. The squares represent those diabetics showing changes in their fundi over the same time period. On the anomaloscope equations the 'change' sample are consistently worse than the 'no change' sample. Although the trend is apparent in all equations, it is only in the blue/green equation that these differences become significant for the youngest and oldest age groups (Kolmogorov Smirnov Test). One explanation for the lack of significance in other equations may be the small numbers involved. Although nearly 300 diabetics were rechecked only 74 of them changed category over the five years. When this number was split into three age groups the resulting sizes may not have been great enough to enable significance to be reached, although a trend was apparent in all cases.

The results for the 100 hue test do not show significance between the change and no change group (Kolmogorov Smirnov), although the scores of both groups are well above normal. The duration variable shows a clear distinction between the change and no change groups, but it was only at the youngest age level that the difference became significant. However, there is an additional problem concerning duration. It is a variable which is particularly difficult to establish in the case of older diabetics because older patients, in contrast to young patients, do not have a dramatic crisis marking the onset of the disease. It is thought/

thought that except for juvenile diabetes, it is quite possible for the condition to have existed in a covert state for many years before diagnosis.

Inspection of Figs. 101 and 102 would suggest that it was the yellow/blue, blue/green equations and duration of diabetes which were helping to discriminate between those diabetics who would, and those who were unlikely,to change. However as only the blue/green equation and duration had revealed significant differences between the two groups, these two variables were used in the subsequent prediction.

Prediction of Retinopathy

This was carried out by first compiling a table of probabilities, and then applying Bayes' theorem to these probabilities. The procedure was as follows. The diabetics were split into three age groups, and into two groups of conditions, i.e. change and no change, at each age. Criterion scores were then selected in each age group for the blue/green matching range and duration. For the blue/green matching ranges the 95th percentile score of the normal population was used at the three age groups, resulting in criterion scores of 12 j.n.d.'s for under 30's, 16 j.n.d.'s for the 30 - 50 year group, and 20 j.n.d.'s for the over 50 year group. Criterion scores for duration for the same three age groups, were five years, eight years and eight years respectively.

Patients in each of the six subgroups were then/

TABLE XIX

	Condition	p(condition)	Conditional probabilities for Ch and Nch	
			p(G-B range > 12 j.n.d.)	p(duration > 5 ye
< 30 Years	Change (Ch) (N = 25)	.19	.44	.88
	No Change (Nch) (N = 107)	.81	.12	.38

	Condition	p(condition)	Conditional probabilities for Ch and Nch	
			p(G-B range > 16 j.n.d.)	p(duration > 8 yea
30-50 Years	Change (Ch) (N = 34)	.33	.42	.71
	No Change (Nch) (N = 69)	.67	.28	.48

	Condition	p(condition)	Conditional probabilities for Ch and Nch	
			p(G-B range > 20 j.n.d.)	p(duration > 8 yea
> 50 Years	Change (Ch) (N = 15)	.38	.60	.67
	No Change (Nch) (N = 24)	.62	.20	.47

then scored as either above or below criteria on the two predicting variables. Consequently, for each subgroup it was possible to give the probability (p) of an individual member of the subgroup being beyond the criterion on each of the predicting variables. (The probability of the individual being within criterion is simply (1-p)). These probabilities, together with the incidence of the event or condition to be predicted in the population, are presented in Table XIX . They form the basic data upon which the Bayesian theorem operates.

The logic of the Bayesian method is based on conditional probabilities, i.e. of estimating the likelihood of an event occurring (e.g. 'change') in the presence of another event (e.g. blue/green matching range beyond the 95th percentile). The event to be predicted y_1 is a member of a set of mutually exclusive events y_1, y_2, ... y_k. A predicting variable x_1 can be a member of an unlimited set x_1, x_2, ... x_j.

The general equation is:-

$$Py_1(x_1x_2 \ldots x_j) = \frac{Py_1 . Px_1/y_1 \ldots Px_j/y_1}{\sum_{\text{all } k} Py_k Px_1/y_k \; Px_2/y_k \ldots Px_j/y_k} \qquad \text{Equation 1}$$

where $Py_1/(x_1x_2 \ldots x_j)$ is read as the probability of event y_1 given predicting variables $x_1x_2 \ldots x_j$ and where the incidence of an event y_1 in the population under consideration is Py_1, and where the incidence of/

TABLE XX

BAYSIAN PREDICTION OF THE LIKELIHOOD OF AN INDIVIDUAL DIABETIC BELONGING TO THE CHANGE GROUP (pch) OR NO CHANGE GROUP (pNch) GIVEN ANY COMBINATION OF PREDICTING VARIABLES

Age		No Knowledge other than incidence of condition in population	Knowledge of Duration		Knowledge of BGMR		Knowledge of both duration and BGMR			
			Duration beyond Criterion	Duration within Criterion	BGMR beyond Criterion	BGMR within Criterion	Duration beyond Criterion /BGMR within Criterion	Duration within Criterion /BGMR beyond Criterion	Duration within Criterion /BGMR within Criterion	Duration beyond Criterion /BGMR beyond Criterion
<30	pch	0.19	0.35	0.06	0.46	0.13	0.26	0.15	0.03	0.67
	pNch	0.81	0.65	0.94	0.54	0.87	0.74	0.85	0.97	0.33
30-50	pch	0.33	0.42	0.22	0.43	0.28	0.37	0.29	0.18	0.52
	pNch	0.67	0.58	0.78	0.57	0.72	0.63	0.71	0.82	0.48
>50	pch	0.38	0.47	0.27	0.65	0.23	0.30	0.53	0.16	0.72
	pNch	0.62	0.53	0.73	0.35	0.77	0.70	0.47	0.84	0.28

pch = probability of change
pNch = probability of No change
BGMR = Blue Green Matching Range

BGMR criterion Age <30 - 12 j.n.d.'s
30-50 - 16 j.n.d.'s
>50 - 20 j.n.d.'s

Duration criterion Age <30 - 5 years
30-50 - 8 years
>50 - 8 years

of each of the predicting variables in each of these events is (Px_1/y_k Px_2/y_k etc.).

This formula may be applied to the probabilities in Table XIX , to obtain the probability of the event given that the predicting variables have exceeded criterion. In order to deal with the situation where an individuals' score is within criterion, the general formula following from Equation 1 is:- Equation 2

$$Py_1/(x_1, \bar{x}_3 \ldots x_j) = \frac{Py_1 \; Px_1/y_1 (1 - Px_3/y_1) \ldots Px_j/y_1}{\sum_{\text{all } k} Py_k \; Px_1/y_k \; (1 - Px_3/y_k) \ldots Px_j/y_k}$$

in which $\bar{x}_3$ indicates that the event x_3 is not present i.e. that the individual is not beyond criterion on this variable and, consequently, that he is within criterion.

In the present study y takes two values, namely 'change' and 'no change', and x takes two values, namely duration and blue/green matching range. Probabilities calculated from Equations 1 and 2 for all combinations of variables and for three age groups are given in Table XX. The first column in this Table gives the incidence of the 'change' and 'no change' groups in each of three age populations. This is simply a frequency count of those in the original sample who now fall into 'change' and 'no change', (without this follow-up data, where no information at all is available, the probabilities of 'change' and 'no change' would each be 0.5). Given/

Given no information other than the frequencies in the two categories, the best bet would be that the diabetic would show no change in a five year period, (e.g. in the young age group p Nch = .81 against pch = .19, so that there is over four times the likelihood of belonging to the Nch group).

The explanation of other cells in the Table proceeds in the same way. If a patient under 30 years is known to have been a diabetic for more than five years, the probability of his changing in the next five years is 0.35, and of his not changing is 0.65. Therefore, the best bet is again that he will not change although now the likelihood is less than 2:1 in this direction.

The fact that the decision is still the same i.e. that he will not change should not be taken to imply that we have no additional information and therefore, are no better off. The incidence of change is less than 20%, and therefore the odds are initially well biased against change. The new information has reduced this bias from over 4:1 to 2:1. Conversely, when only duration is known and is within criterion, the probability of a young diabetic developing retinopathy over five years is now reduced from 0.19 to 0.05 and the decision that he will not change is now much stronger (p = 0.95).

Suppose that the period of diabetes is uncertain but the patient's blue/green matching range exceeded the 95% cut off point for the general population. The/

The probability of change is 0.46. Consequently, once again the chance of developing retinopathy is increased beyond the basic knowledge at which p = 0.19. For the case where BGMR* is within criterion, the probability of change is reduced from 0.19 to 0.13. Knowledge of both duration and blue/green discrimination increases the power of prediction in the same direction, so that it is not surprising that if knowledge on both variables is available the probability of change can rise to 0.67 when both the blue/green matching range and duration exceed criterion, and be reduced to 0.03 where both variables are within criterion. In the former case the best bet is now that the diabetic will develop retinopathy over the five year period.

In order to clarify Table XX two calculations are carried out to illustrate the computational procedure for two cells of this Table.

a.) Age <30. Both BGMR and duration exceed criteria.

$$pch = \frac{.19 \times .44 \times .88}{(.19 \times .44 \times .88) + (.81 \times .12 \times .38)} = 0.67$$

b.) Age <30. BGMR beyond criteria; duration within criteria.

$$pch = \frac{(.19 \times .44 \times (1 - .88))}{(.19 \times .44 \times (1 - .88)) + (.81 \times .12 \times (1 - .38))} = 0.15$$

(See Table XIX for basic probabilities).

For each age group the probability of change is much higher when information about both duration and/

* Blue/Green Matching Range

and blue/green sensitivity is known. Blue/green is a better prediction of change than duration for the youngest group, but vice versa in the oldest group. In the 30 - 50 year age group there is no difference between duration and blue/green sensitivity in prediction (0.42: 0.58; 0.43: 0.57). However, using both variables together as predictors is more advantageous than using one alone (0.52 : 0.48). In all cases when both variables exceed criteria the probability of change is increased; when neither variable exceeds criteria the probability of change is very small.

It is hoped that Table XX will help towards distinguishing those diabetics who require regular follow-up studies, and those who need less frequent attention from the point of view of their retinal states. It should be emphasised that these predictions of fundus change are only meant to act as a guide. The Table may be deficient on two grounds. Firstly, there may be other clinical or psychophysical variables which could be added to the battery to improve prediction. Secondly, there may well be more appropriate cut off points for both duration of diabetes and blue/green sensitivity, which might make better use of the available information. The importance of the present work is to show that it is possible to predict deterioration in the fundi of diabetics, from knowledge of an individual's colour vision./

vision.

It is worth recording that these predictions were based on an original system of measurement which made use of the method of limits. The results are impressive given the inherent problems in this measurement (See Section II), and suggest that further predictions could be given using the same variables but improving the method of testing. In addition, the subjective nature of the fundal assessment should not be forgotten in this study. Although general agreement was reached on what consitituted membership of the four different categories, the clinician carrying out the recheck was not the one who made the original classification.

With these points in mind, a further study was carried out on a group of young diabetics. This included other psychophysical variables and alternative test procedures. The basic questions were to examine whether diabetics were performing differently on these tests from normals; if there were differences were the differences simply reflecting once more the anomaloscope changes, or were additional factors present which might ultimately be added to the prediction battery?

2. Comprehensive Analysis of Macular and General Function

(i) General Findings

Method

A group of 33 young diabetics (average age = 27 years) were selected for this analysis on the grounds of having/

having good acuity and no retinopathy. (The number was relatively small because of the difficulty in persuading the patients to undergo such a lengthy series of tests). The battery of tests used was, the Ishihara Plates; Farnsworth Munsell 100 hue test; Pickford Nicholson anomaloscope (3 equations); Dark adaptation; Static perimetry at high luminance; Foveal spectral sensitivity curve; Wavelength discrimination at 495 nm. The tests were administered in two test sessions each lasting approximately 1½ hours. Three subjects were not included in the analysis because of their failure to complete the full test battery. The tests were given in a random order (except for the Ishihara Plates and the 100 hue test which were always given first as introductory tests) so that effects of fatique or familiarisation should not accumulate on any one test.

Results

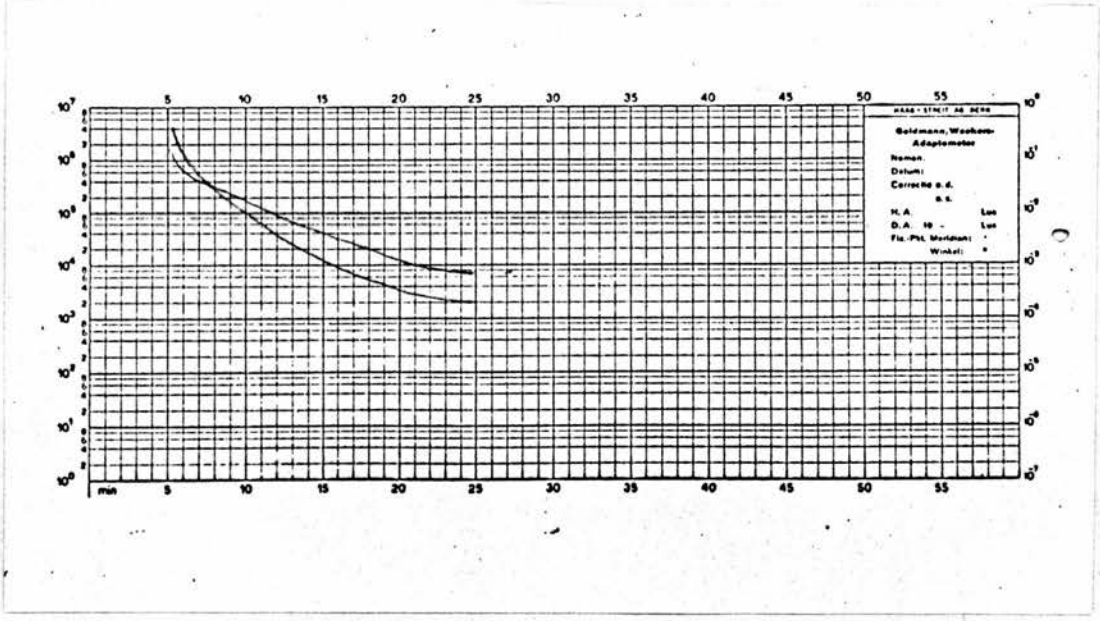
The Ishihara, 100 hue test and anomaloscope results have been given for the larger sample in the last section and this data is consequently a more reliable index of diabetic performance. The present results on these tests largely confirm the former ones. A comparison of means between the normal and diabetic populations showed the following features. The Ishihara test showed no significant difference between the normal and diabetic groups. The 100 hue test also showed no significant difference between the two groups, with/

with a mean diabetic score of 73 in comparison to a mean score of 40 for the corresponding normal age group (Table II). The anomaloscope results showed significant differences on the yellow/blue and blue/green equations and no significance, although an extended matching range, on the red/green equation.

Of the additional tests in the battery, the wavelength discrimination was extended but not significantly different from normal, although the mid-matching point was shifted significantly towards the blue. This was a new piece of evidence not brought out by the anomaloscope where, as in the original study no significant shifts in mid-matching point were detected. The photopic luminosity was examined after transformation of the data by means of Table XI. No significant differences were apparent at any of the seven selected points for the determination of $V\lambda$.

On the other hand the dark adaptation data was particularly interesting. From the best fitting dark adaptation curves, thresholds were measured at 4, 12 and 20 minutes for both yellow/green and blue/green targets. The cross-over point, and the mean cone and rod separations, were also recorded for analysis. A comparison of the absolute levels of the threshold at each of the times after preadaptation showed that while there was a tendency for the diabetic thresholds to be above those of the normals, none of the differences/

An Early and a Normal Cross Over Time in Two Diabetic Patients



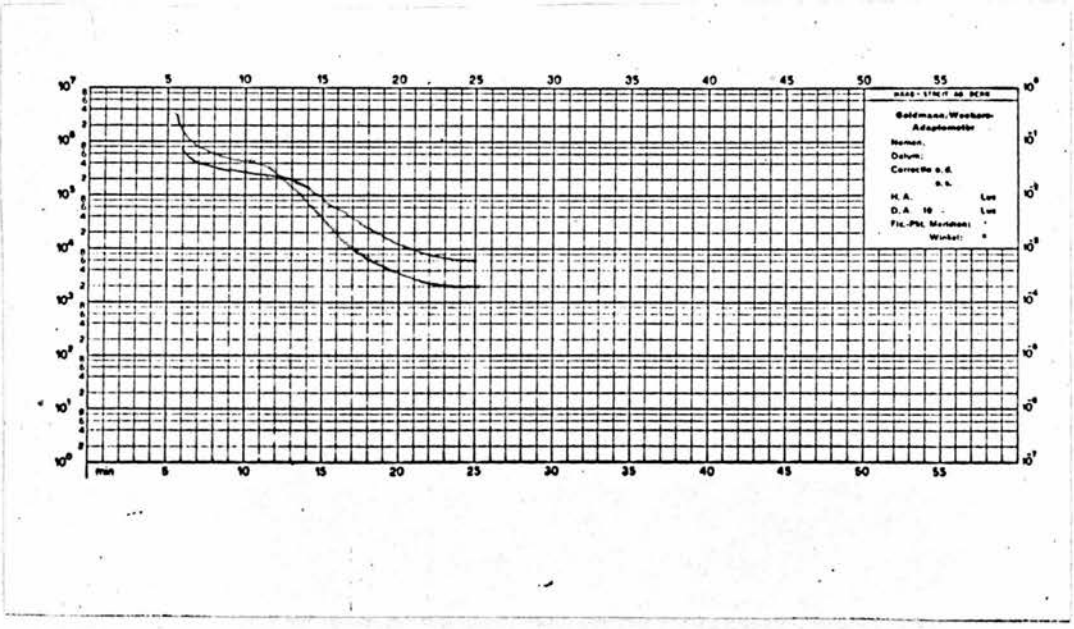


Figure 103

differences were significant. The cone separation of the diabetic group (2.3) was larger than that of the control group (2.2), and the rod separation of the diabetics (4.50) was smaller than that of the controls (4.80). Although neither of these differences were significant the trend was interesting and suggested that the blue/green thresholds had been affected more than the yellow thresholds in diabetes. Consequently in cone vision, where the blue/green curve lies above the yellow/green, the resulting separation is increased, and in rod vision, where the blue/green curve lies below the yellow/green curve, the resulting separation is reduced.

A comparison of the cross-over times between the diabetic group (mean = 4.17) and the normal groups (mean = 5.8) did reach significance ($t = 2.24$, $p < .05$) so that the diabetic group did have significantly earlier cross-over times than normals. Therefore in the diabetic eye, the rods take over from the cones at an earlier stage in the dark adaptational process than they do in the normal eye. This finding is of particular interest and the possibility of a relationship between early cross-over time and colour vision results is dealt with in detail on page 320. Fig.103 shows a typical example of an early cross-over time in dark adaptation in one diabetic patient, and a normal cross-over point in another patient in the group./

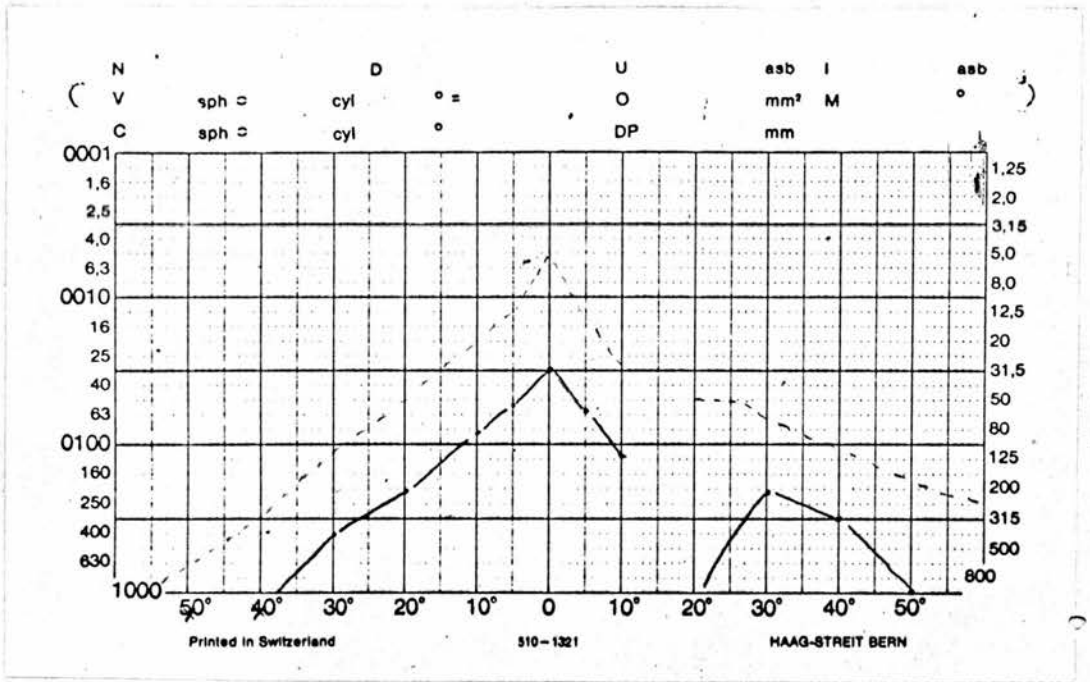


Figure 104 General Perimetric Losses

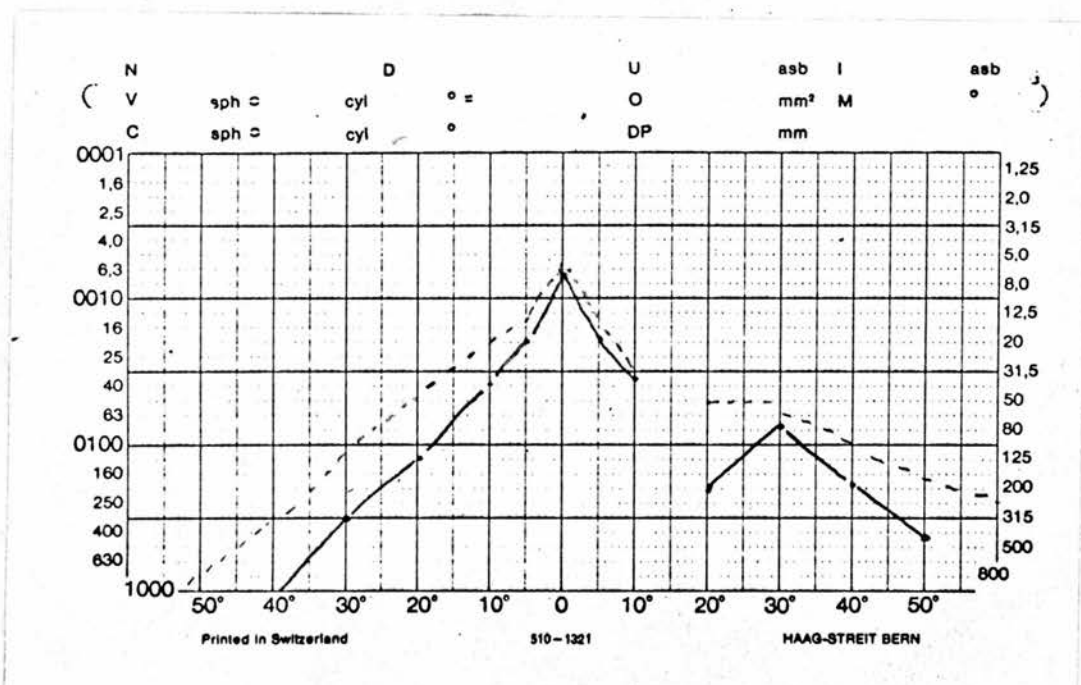


Figure 105 Peripheral Perimetric Losses

group.

Static perimetry in thresholds were measured at 50°N, 40°N, 30°N, 20°N, 10°N, 5°N, Fovea, 5°T, 10°T, 20°T, 30°T, 40°T, 50°T. At all points, the mean diabetic values were lower than those of the normals. Significant differences from Fig. 72 were found at 5°N, 5°T, 20°T, 40°T, 50°T. In addition to the mean diabetic thresholds showing change, there were unique features in several of the diabetic threshold gradients not encountered in normal subjects. Some individuals had a general lowering of the whole gradient at all points tested. Fig.104 shows a typical example of such a case. Other patients had losses restricted to the peripheral regions with normal function within 15° of the fovea. Fig.105 is an example of this second type. Again some patients had losses restricted to the central regions (Fig.106). The diabetic population as a whole showed more irregularities in their threshold gradients. Fig. 107 illustrates this for one patient in the group. Furthermore this observation was borne out by several low correlation coefficients between scores at adjacent retinal points (See below).

In conclusion the following general points may be noted in gross comparison between the two populations. Firstly, the colour vision results in the small sample are similar to those previously found in the larger diabetic sample. They confirm reduced vision in all/

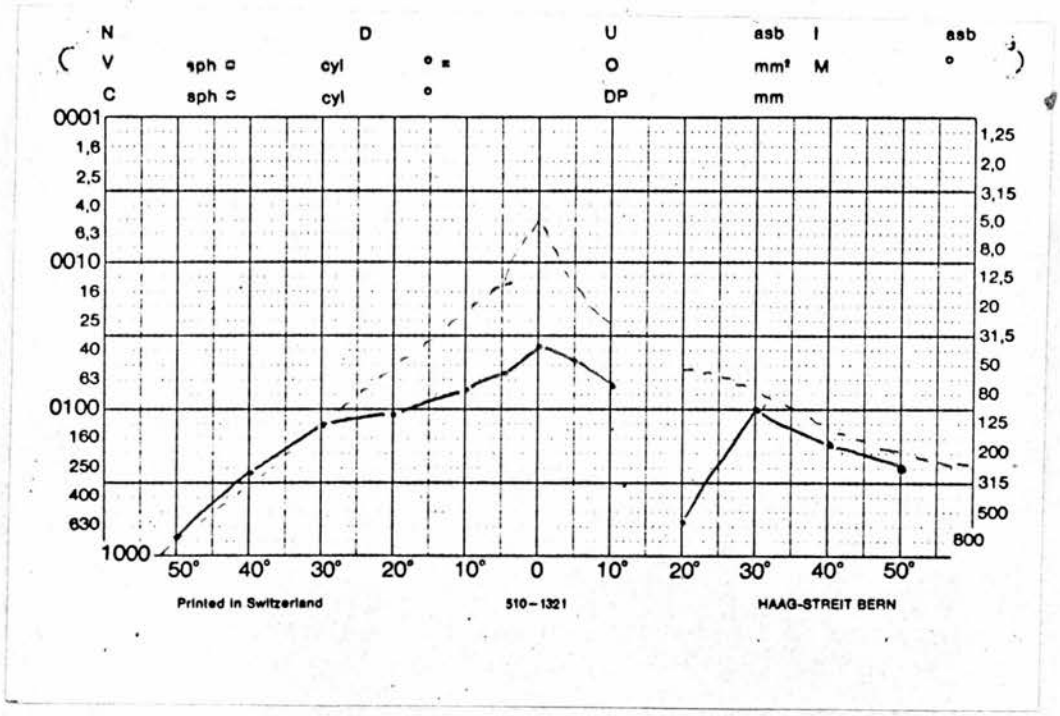


Figure 106 Central Losses

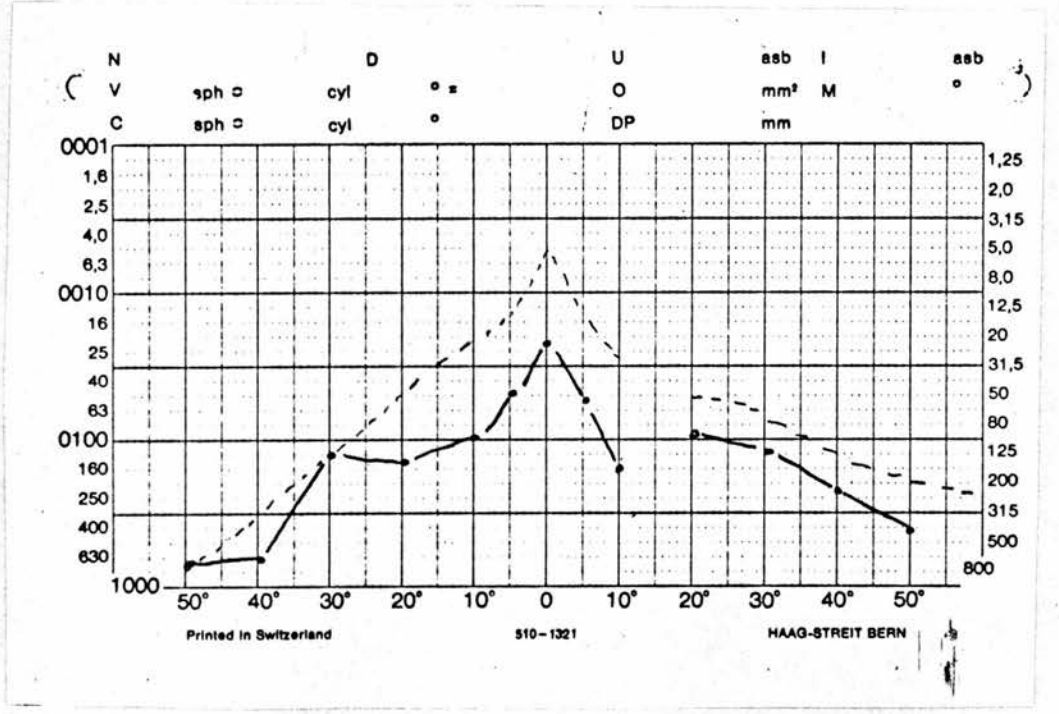


Figure 107 Irregular Losses

all cases, which reaches significance in the anomaloscope yellow/blue and blue/green equations. Of the additional tests administered to the smaller sample, the wavelength discrimination at 495 nm. indicated an extended matching range, although still within normal limits, and a mid-matching point which was significantly shifted towards the blue end of the spectrum. The photopic luminosity curve did not show any significant changes from that in the normal eye. Of the tests of general function the dark adaptation thresholds were raised, but the only significant difference was in an early cross-over time. Perimetric data at high luminance showed significant reductions, particularly in the temporal retina. Irregularities in the threshold gradient were observed, together with a general reduction of vision in some patients, a peripheral loss in some patients, and a central loss in some patients.

(ii) Factor Analysis

It is apparent that in young diabetics without retinopathy it is possible to detect changes in visual function on nearly every test included in this battery. The question arises as to whether it is the same source of variation which is responsible for the losses on each of the tests (i.e. the tests are highly correlated with each other and are all measuring losses from a common source) or whether different sources of variation are responsible for losses on different tests (i.e. some/

some tests are not correlated and therefore they are measuring losses from different source variables).

One of the ways of answering this question is by means of factor analysis. In factor analysis the underlying patterns and relationships in the data are examined. The number of factors necessary to account for these inter relations represent the sources of variation in the data. If each test only measured something unique to itself, there would be as many factors as tests. However more commonly, the number of factors is smaller than the number of tests in the battery, indicating that correlations exist between the tests. For a detailed explanation of the method see HARMAN (1967).

Method

As the factoring method chosen for this analysis operates on Pearson product moment correlation coefficients, the assumptions necessary for these correlations must be met. An examination of the skewness of the frequency distribution for each variable, revealed that only the Ishihara scores failed to meet the normality criterion. However because of the popular use of this colour vision test, and because it was the only test failing to meet the criterion, it was thought desirable to maintain it in the battery but to exercise caution in its interpretation.

The method of factor analysis selected to operate/

TABLE XXI

CODE FOR COMPUTER VARIABLES

1.	ISH	Ishihara
2.	HA	100 hue box A
3.	HB	" " B
4.	HC	" " C
5.	HD	" " D
6.	HT	" " Total
7.	INC	increment threshold
8.	BI	Dark Adaptation Blue threshold 4 mins.
9.	YI	" " Yellow " " "
10.	BT	" " Blue " 12 "
11.	YT	" " Yellow " " "
12.	BF	" " Blue " 20 "
13.	YF	" " Yellow " " "
14.	CO	cross over
15.	RGMR	red/green matching range
16.	RGMMP	red/green mid matching point
17.	YBMR	yellow/blue matching range
18.	YBMMP	yellow/blue mid matching point
19.	BGMR	blue/green matching range
20.	BGMMP	blue/green mid matching point
21.	HMR	Helmholtz matching range
22.	HMMP	Helmholtz mid matching point
23.	N50	Static Perimetry Nasal Field 50°
24.	N40	" " " " 40°
25.	N30	" " " " 30°
26.	N20	" " " " 20°
27.	N10	" " " " 10°
28.	N5	" " " " 5°
29.	T5	" " Temporal " 5°
30.	T10	" " " " 10°
31.	T20	" " " " 20°
32.	T30	" " " " 30°
33.	T40	" " " " 40°
34.	T50	" " " " 50°
35.	VV	Photopic V_λ 426 nm.
36.	VB	" " 464 nm.
37.	VT	" " 496 nm.
38.	VG	" " 531 nm.
39.	VP	" " 560 nm.
40.	VY	" " 590 nm.
41.	VR	" " 650 nm.
42.	BYBAXIS	Bipolar 100 hue axis
43.	MYBAXIS	Monopolar 100 hue axis
44.	CONESEP	cone separation
45.	RODSEP	rod separation

operate on correlations between variables (R factoring) was the Principal Component Analysis. This gives the linear combination of variables which takes account of most of the variance in the data. No assumptions about the underlying structure of the variables is required. The first component represents the best single summary of linear relationships in the data. The second component, which is orthogonal to the first, represents the best linear summary of the remaining variance. The process is repeated until most of the variance in the data is accountable. Following the initial extraction of factors the orthogonal rotation (Varimax) was carried out. The purpose of rotation is to simplify factor patterns, so that variables are loaded highly with some factors but not with others.

Factor Loadings

The variable list included 41 data points for each individual, plus 4 computed variables (e.g. cone separation). The forty-five variables are listed in Table XXI , together with their abbreviations used for computer output. In the 45 x 45 correlation matrix, over 300 correlations were significant at the $p < .01$ probability level.

The initial factor matrix is presented in Table XXII. All factors with an associated eigen value of less than 1.0 (i.e. the variance in the data accounted for by these factors is less than 1%) have been deleted, leaving 10 factors which account for 97% of the variance in the/

FACTOR MATRIX USING PRINCIPAL FACTOR WITH ITERATIONS

	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4	FACTOR 5	FACTOR 6	FACTOR 7	FACTOR 8	FACTOR 9	FACTOR 10
ISM	0,03092	-0,20561	0,18499	0,41662	-0,43412	-0,21588	-0,24173	-0,06342	-0,15354	-0,13454
MA	-0,07405	0,32983	0,28305	0,00131	-0,55596	0,28995	0,19947	-0,15832	-0,03962	0,29246
MB	0,08206	0,55501	-0,17469	0,17796	-0,52467	-0,09442	0,32643	-0,10123	-0,03884	-0,22487
MC	0,03025	0,71221	-0,03752	-0,19434	-0,55019	0,05146	-0,09296	0,28229	-0,13044	-0,07446
MD	-0,03770	0,22924	0,04328	0,49573	-0,73368	-0,13118	0,07716	-0,16291	0,05829	0,12477
MT	0,89867	0,41391	-0,04722	0,15650	-0,06381	0,01984	0,10787	0,03756	0,08484	0,03641
INC	-0,66447	0,42296	-0,23672	-0,16231	-0,17443	-0,19893	-0,16069	-0,03964	0,20999	-0,09308
BI	-0,88993	-0,00195	0,16984	0,12240	0,08475	0,28472	0,04420	0,06996	0,20781	0,22755
YI	-0,82828	0,14534	0,14141	0,02533	0,37457	0,24222	-0,05709	-0,14449	0,07782	0,32253
BT	0,63987	0,31316	-0,16755	0,09700	0,11909	0,08910	0,14407	-0,19421	0,07572	0,21515
YT	-0,80268	-0,03407	0,21344	-0,08562	0,12237	-0,02359	0,01874	-0,34469	-0,04967	-0,06565
BF	-0,69009	0,06834	0,17523	-0,02084	0,20697	0,11741	0,22229	-0,31847	-0,02931	-0,21457
YF	0,91950	0,32107	-0,08503	0,17326	0,15997	0,19974	0,18542	0,01864	0,07993	-0,08987
CO	-0,69247	0,01504	0,04712	0,19810	-0,29517	0,15870	0,10081	0,39237	0,21314	0,19448
RGMR	-0,02061	0,13686	0,39858	-0,11445	-0,57019	0,37998	-0,32141	-0,41682	-0,10098	-0,11938
RGMMP	0,91920	0,16219	-0,15064	0,15281	-0,02683	-0,17518	0,00837	0,02651	-0,01576	0,06917
YBMR	0,82298	0,38487	-0,23262	-0,06219	-0,02420	0,05540	-0,21841	-0,02148	-0,00645	0,06538
YBMMP	0,80231	0,32533	-0,03016	-0,12886	0,17854	0,19586	0,07525	-0,11288	0,09616	0,20300
BGMR	0,78451	0,47459	-0,15785	-0,02743	0,01942	0,06137	-0,16788	0,12009	-0,00866	0,03648
BGMMP	0,91809	0,25969	0,01790	-0,04820	-0,02035	-0,11687	0,07654	-0,12065	0,22295	0,13817
MMR	-0,49250	0,46589	-0,32977	-0,12789	0,05554	-0,03934	0,03008	-0,12130	0,17165	-0,30746
MMMP	0,92232	0,12297	-0,22566	0,06997	-0,06880	-0,02986	0,13420	-0,02466	0,18558	0,15143
N50	-0,06493	1,81719	1,60204	0,52935	0,53633	0,01698	-0,07440	0,09294	0,04553	-0,11776
N40	0,23837	0,42891	-0,30703	0,15656	0,09080	0,23880	0,10482	-0,20417	-0,23938	-0,16157
N30	0,04633	0,43620	-0,26684	0,08352	-0,04621	0,50882	-0,38109	-0,23282	-0,17719	0,17110
N20	-0,31474	0,60897	-0,35796	-0,37382	-0,04096	0,13788	-0,26711	-0,25662	0,01572	0,02649
N10	-0,24848	0,42092	-0,46827	-0,25398	-0,17791	-0,17279	-0,02731	-0,02473	0,06988	-0,00374
N5	-0,34708	0,66209	-0,30331	-0,25648	-0,18990	-0,05604	-0,09520	-0,07797	0,36790	0,04615
T5	-0,51078	0,65590	-0,39739	-0,12511	0,01507	-0,17188	0,09384	-0,09448	0,22690	-0,10574
T10	-0,31858	0,66317	-0,34630	-0,32101	0,00749	-0,20066	0,09067	-0,11747	0,19785	-0,06694
T20	-0,47220	0,50648	-0,12712	0,39456	-0,03255	-0,13965	0,51473	-0,02854	-0,61567	0,10294
T30	-0,32563	0,64368	-0,27895	-0,22793	0,11620	-0,00303	0,42316	-0,02005	0,02456	0,20652
T40	-0,29986	0,42877	-0,38684	-0,43464	0,16041	-0,31805	0,32516	0,33738	-0,16954	-0,04466
T50	-0,24392	0,35457	-0,20637	-0,54920	0,18209	-0,16430	-0,26348	-0,02780	-0,41500	0,30621
VV	-0,17617	-0,00534	-0,69705	0,34044	0,10004	1,02397	0,11621	0,27709	0,00818	-0,32343
VB	-0,26428	0,22937	-0,11164	0,76291	0,01873	-0,27895	-0,32991	0,28096	0,02558	0,01993
VT	-0,23916	0,22015	-0,20789	0,65468	-0,06523	-0,34340	-0,31603	0,09028	0,01404	-0,00214
VG	-0,28054	0,26263	-0,55822	0,51828	0,17811	-0,00679	-0,10490	-0,08384	-0,00424	0,16888
VP	-0,41391	0,15539	-0,67469	0,48953	0,03778	-0,00117	-0,09658	0,07545	-0,08918	0,23151
VY	0,05455	0,04471	-0,75318	0,18754	0,46668	-0,04387	-0,37443	-0,04222	0,04109	-0,07369
VR	-0,30544	0,29257	-0,68482	0,47754	0,03241	0,04641	0,12942	-0,09119	-0,07441	-0,03669
BYBAXIS	-0,02987	0,47368	0,21837	-0,56041	-0,10865	0,31473	-0,12579	0,29527	-0,13837	0,11687
MYBAXIS	0,04770	0,64959	-0,07411	-0,40529	-0,18619	0,04775	-0,27056	0,44949	-0,15018	-0,17831
CONESEP	-0,76671	-0,16135	0,15772	0,17782	-0,23876	0,22043	0,13342	0,23842	0,27070	0,12870
RODSEP	0,94373	0,17553	-0,21719	0,09222	0,00214	0,11648	0,11477	0,06253	0,05484	0,35029

TABLE XXII

TABLE XXIII

VARIABLE	COMMUNALITY	FACTOR	EIGENVALUE	PCT OF VAR	CUM PCT
ISM	0.59015	1	13.78273	29.2	29.2
MA	0.73952	2	9.92263	21.0	50.3
MB	0.82824	3	6.99448	14.8	65.1
MC	0.96346	4	4.53753	9.6	74.7
MD	0.90854	5	3.15678	6.7	81.4
MT	1.03169	6	2.65237	5.6	87.0
INC	0.85294	7	1.98534	4.2	91.2
BI	1.02586	8	1.63132	3.5	94.7
YI	1.06101	9	1.37827	2.9	97.6
BT	0.91964	10	1.13123	2.4	100.0
YT	0.83931				
BF	0.76362				
YF	1.10049				
CO	0.88087				
RGMR	0.96212				
RGMMP	0.95456				
YBMR	0.93955				
YBMMP	0.90615				
BGMR	0.91452				
BGMMP	1.01626				
MMR	0.72695				
MMMP	1.00323				
N50	0.47119				
N40	0.56092				
N30	0.79173				
N20	0.89661				
N10	0.59046				
N5	0.90841				
T5	0.97484				
T10	0.87022				
T20	1.32728				
T30	0.88635				
T40	0.98915				
T50	0.92577				
VV	1.89056				
VB	0.94548				
VT	0.80779				
VG	0.80624				
VP	0.96819				
VY	0.97609				
VR	0.90997				
BYBAXIS	0.83200				
MYBAXIS	0.96015				
CONESEP	0.94018				
ROUSEP	1.01328				

VARIMAX ROTATED FACTOR MATRIX

	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4	FACTOR 5	FACTOR 6	FACTOR 7	FACTOR 8	FACTOR 9	FACTOR 1
ISM	-0,08946	-0,35234	-0,07478	0,34344	0,42940	-0,15255	0,01851	-0,14413	-0,08354	-0,31453
HA	-0,01748	0,07142	0,11665	-0,20113	0,72520	-0,01154	0,10975	0,14166	0,22671	0,26549
HB	0,28052	0,42827	0,04131	0,12705	0,61821	0,15528	0,07730	0,26931	-0,16734	-0,18838
HC	0,19997	0,43942	0,06268	0,02147	0,46935	0,02723	0,70386	0,07670	0,15207	-0,13161
HD	0,66373	0,05461	-0,04314	0,38125	0,85908	-0,07405	-0,07185	0,03444	-0,05997	0,03293
HT	0,98309	-0,03931	0,16665	0,00983	0,16284	0,04381	0,06993	0,02869	-0,04073	0,01361
INC	-0,43493	0,75326	0,00582	0,22641	0,10489	-0,08925	0,14171	-0,09208	0,02379	-0,09463
BI	-0,81418	0,14296	0,22302	0,11230	0,04895	0,16178	-0,07495	-0,00517	0,10469	0,48477
VI	-0,71364	0,23135	0,33898	0,09105	-0,17599	0,01269	-0,15667	0,10784	0,37608	0,40773
BT	0,92616	0,02744	0,13900	-0,04701	-0,00132	0,05043	-0,17464	0,05988	0,05963	-0,07397
VT	-0,79827	0,22372	0,20403	-0,06828	0,00879	-0,10164	-0,23470	0,09182	0,15617	-0,18616
BF	-0,65590	0,24642	0,32075	-0,13359	-0,00467	0,14083	-0,28003	0,19512	1,07057	-0,17369
VF	0,97542	-0,11326	0,23080	-0,07272	-0,02451	0,26806	-0,03531	0,05321	-0,02509	-0,02254
CO	-0,00304	0,11115	-0,01090	0,23985	0,28734	0,18927	0,18913	-0,01819	-0,18502	0,50841
RGMR	-0,12916	-0,06250	0,13901	-0,27571	0,65645	0,00459	0,14697	-0,29825	0,48239	-0,26834
RGMRP	0,94249	-0,16461	-0,00024	0,09700	0,02178	-0,10852	0,00907	0,01789	-0,07022	-0,09247
YBMR	0,90518	0,06584	-0,02317	0,02005	-0,01764	-0,01305	0,19658	-0,09997	0,24161	-0,18624
YBMRP	0,86047	-0,00468	0,15587	-0,25607	-0,07658	0,02882	-0,02688	0,08954	0,22031	0,14338
BGMR	0,88369	0,06809	0,10094	0,04304	-0,03421	0,02157	0,29790	-0,04764	0,15231	-0,13285
BGMRP	0,95553	-0,01387	0,08671	-0,16317	0,08492	-0,19395	-0,09028	-0,11469	0,03367	0,04451
HMR	-0,25240	0,75605	0,12001	0,11847	-0,04645	0,20588	0,00295	0,03566	0,00799	-0,13893
HMRP	0,97133	-0,07587	-0,13761	-0,04289	0,06553	0,00406	-0,11325	-0,05678	-0,06838	0,09435
N50	0,18850	0,24147	2,37885	0,19183	0,38795	-0,37283	0,53886	0,25830	0,13424	0,13434
N40	0,38672	0,20256	0,12076	0,09962	0,03820	0,35006	-0,02365	0,31351	0,27416	-0,21866
N30	0,19050	0,17854	0,05058	0,18482	0,11750	0,27523	0,15994	0,30420	0,75564	0,42664
N20	-0,06782	0,76673	0,00256	-0,00076	0,00002	0,03398	0,19431	-0,01316	0,51273	-0,04623
N10	-0,61025	0,69970	-0,22131	0,12092	0,04226	-0,02712	0,15983	-0,07550	0,05619	-0,01577
N5	-0,03856	0,88558	0,05508	0,09712	0,16146	-0,01943	0,15020	-0,13416	0,12713	0,16761
T5	-0,16844	0,93034	0,11438	0,20973	0,01186	0,06475	0,01932	0,13433	-0,00523	0,03271
T10	-0,01046	0,91625	0,07880	0,02224	-0,01757	-0,05375	0,07842	0,11822	0,02441	0,06654
T20	-0,24477	0,23797	0,17841	0,36449	0,27596	0,06394	0,02732	0,98240	0,00977	-0,02544
T30	-0,01171	0,72433	0,12572	-0,06731	-0,01161	0,05179	0,03780	0,48819	0,05334	0,39952
T40	-0,07065	0,65365	-0,12040	-0,05410	-0,51519	-0,06295	0,34688	0,49474	-0,26093	0,44684
T50	-0,12446	0,41414	-0,13917	-0,07455	-0,32551	-0,39572	0,38049	0,30176	0,46393	-0,41456
VV	-0,07347	0,00484	-0,24522	0,19272	-0,14447	1,30821	0,05668	0,04483	0,21202	0,15299
VB	-0,11277	-0,00174	0,21078	0,93515	0,07187	-0,02059	0,04532	-0,01936	-0,07387	0,11631
VI	-0,07931	0,09964	0,08210	0,87143	0,11856	-0,07043	0,00250	-0,01797	-0,05304	-0,07151
VG	-0,02658	0,28927	-0,05103	0,71329	-0,09710	0,22000	-0,20556	0,24264	0,23102	0,12741
VP	-0,15980	0,26862	-0,27175	0,76226	-0,06446	0,25543	-0,07594	0,25774	0,18699	0,19765
VY	0,21876	0,25746	-0,23076	0,54084	-0,59594	0,23443	-0,14459	-0,08431	0,24400	-0,13922
VR	-0,02466	0,40275	-0,14633	0,61181	0,02864	0,42311	-0,20167	0,34872	0,10131	-0,00495
BYBAXIS	0,01123	0,23139	0,18723	-0,48662	0,03285	-0,02499	0,68409	0,02765	0,26377	0,19469
MYBAXIS	0,17887	0,43244	0,10545	-0,04563	0,00627	0,02866	0,84532	-0,01372	0,06538	-0,18968

TABLE XXIV

the data. The eigen values associated with the 10 principal factors are given in Table XXIII, together with the percentage of variance (PCT of VAR) and cumulative percentage (CUM PCT). Also in this Table are the communalities of each variable.

The communalities represent the proportion of variance in a variable accounted for by all the factors. This is best explained by reference to the initial factor matrix.

The communality of the Ishihara test (ISH) is given by:-

$$(-0.08946)^2 + (-0.35234)^2 + (-0.07478)^2 + \ldots + (-0.31453)^2 = 0.59015$$

Most of this variance is derived from Factors 2, 4, 5 and 10. It represents the amount of variance of a variable that is shared by at least one of the other variables. The complement of communality represents the uniqueness of a variable, i.e. the proportion of its variance not accounted for by the factors and not shared with the other variables. For the Ishihara, the unique variance = (1 - 0.59015) or 0.40985.

The varimax rotated factor matrix is given in Table XXIV This Table shows that nearly all the variance in the data can be accounted for by ten orthogonal factors. Thus the original forty-five variables, or potentially forty-five factors, have been reduced to ten. Reading across this matrix, each variable can be expressed as/

Figure 108

HORIZONTAL FACTOR 1
VERTICAL FACTOR 2
1 = ISH
3 = MB
5 = MD
7 = INC
9 = YI
11 = YT
13 = YF
15 = RGPR
17 = YBPR
19 = BGPR
21 = HMK
23 = NSP
25 = N30
27 = N10
29 = T5
31 = T2V
33 = T4V
35 = VV
37 = VT
39 = VP
41 = VR
43 = MYBAXIS
45 = ROOSEP
2 = HA
4 = MC
6 = MT
8 = BI
10 = BT
12 = BF
14 = CO
16 = RGMAP
18 = YMAP
20 = BGMAP
22 = HMAP
24 = N40
26 = N20
28 = T5
30 = T1A
32 = T3A
34 = T5A
36 = VR
38 = VG
40 = VV
42 = MYMAXIS
44 = COVESEP

as a regression equation in terms of the ten factors. Therefore, the normalised 100 hue score HT is given by:-

HT = 0.98309 F1 - 0.03931 F2 + 0.16665 + ... + 0.01361 F10

The most important determinant of the 100 hue score is factor 1, and the influence of the other factors is negligible. Each variable can be described in this way and the loading on each factor assessed.

Graphical Presentation of Rotated Orthogonal Factors

The final output of the computer program presents the factor loadings of the rotated factor matrix by plotting all combinations of pairs of factors. This represents the final outcome of the analysis. There are three principal considerations for interpreting the graphs:-

a.) the distance of a variable from the two axes.

b.) the direction of a variable in relation to the axis (so that positive and negative loadings are distinguished).

c.) the relative position of variables to each other (particularly the clustering of variables).

Consider Fig.108 in which factor 1 is plotted horizontally and factor 2 vertically. Variables No. 15, 36, 35, 37, 2, 5 all lie near the origin and therefore, have small loadings on both factors. (See key to the right of the graph and Table XXI for the variable notation). Variables 19, 17, 10, 18, 20, 22, 45 and/

and 16 load high on factor 1 but low on factor 2. Similarly variables 29, 30, 28, 26, 32, 33, 27 load high on factor 2 but low on factor 1. There is little correlation between the variables of one cluster and the variables of the other, as the clusters lie close to orthogonal axes. However, variables within a cluster correlate highly with each other and as they share the same factor loading can be said to be measuring the same source variation.

A further cluster evident in Fig.108 is that containing variables 8, 11, 9, 12, 14, 44. This cluster is loaded highly, but negatively, on factor 1. In other words there is a strong negative relationship between these variables and the variables in cluster 19, 17, 10, 18, 20, 22, 45 and 16. Inspection of the variables loading highly on factor 1 shows that the BGMR, YBMR, YBMMP, BGMMP, HMMP, Rod separation, RGMMP, load in the positive direction; and that the initial dark adaptation thresholds, cone separation, and cross-over time load in the negative direction. It is not surprising that the relationship between the cone separation and the rod separation should be a negative one (e.g. as cone separation increases the rod separation decreases). Since the mean cone separation is slightly larger in the diabetic population than in the normal population it appears that the blue/green curve has been most affected, and has moved away from the yellow/

yellow/green curve in the cone section, and towards the yellow/green curve in the rod section.

The significantly early cross-over time in diabetics has been mentioned on page 306. Factor analysis has further revealed that the cross-over point is negatively related to BGMR, YBMR, YBMMP, BGMMP, HMMP, RGMMP and rod separation. There are a preponderance of variables requiring blue discrimination in this list. The BGMR and YBMR variables are simply matching ranges, indicating that loss of discrimination on yellow/blue and blue/green axes are associated with early cross-over times. There is in addition a negative correlation between cross-over time and RGMMP indicating that early cross-over times are associated with shifts towards the shorter wavelengths on the red/green equation. The mid-matching points, BGMMP, YBMMP and HMMP, are coded so that high numbers represent a shift towards the blue. In other words in each of these three discrimination tasks, there is a shift towards the blue end of the matching equation associated with early cross-over times.

As explained in Section IV shifts in mid-matching point represent a loss of sensitivity of one of the fundamental colour mechanisms. In this case it is a loss to blue so that more blue is required in the mixture than would normally be necessary. Therefore, in patients with early cross-over times there is a significantly/

significantly associated loss in sensitivity to blue. It is equally important to note that the red/green discrimination (variable 15) is one of the variables not loading significantly on either factor, and therefore not associated with the cross-over time. It appears, therefore, that there is a special link between colour sensitivity to blue and the transition from cone to rod function in dark adaptation. The physiological implications of this association are discussed below on page 320 . The high correlations between the yellow/blue and the blue/green equations suggest that only one is necessary in a test battery. The discussion in the follow-up study (page 294) suggested that the blue/green equation would be selected.

Of the variables loading highly on factor 2, every one in the cluster is a threshold measurement in static perimetry. However, the extreme peripheral values and the threshold adjacent to the blind spot (variables 23, 34, 31) are not highly loaded on either of the two factors. (These thresholds can be unreliable because for the extreme readings fewer people are on scale, and for the 20°T point significantly greater variability exists than for any other threshold (ASPINALL, 1967)). The remaining static perimetry measure, which is foveal increment threshold (variable 7), loads highly on factor 2 and moderately on factor 1. This removes it from the other cluster of increment thresholds although/

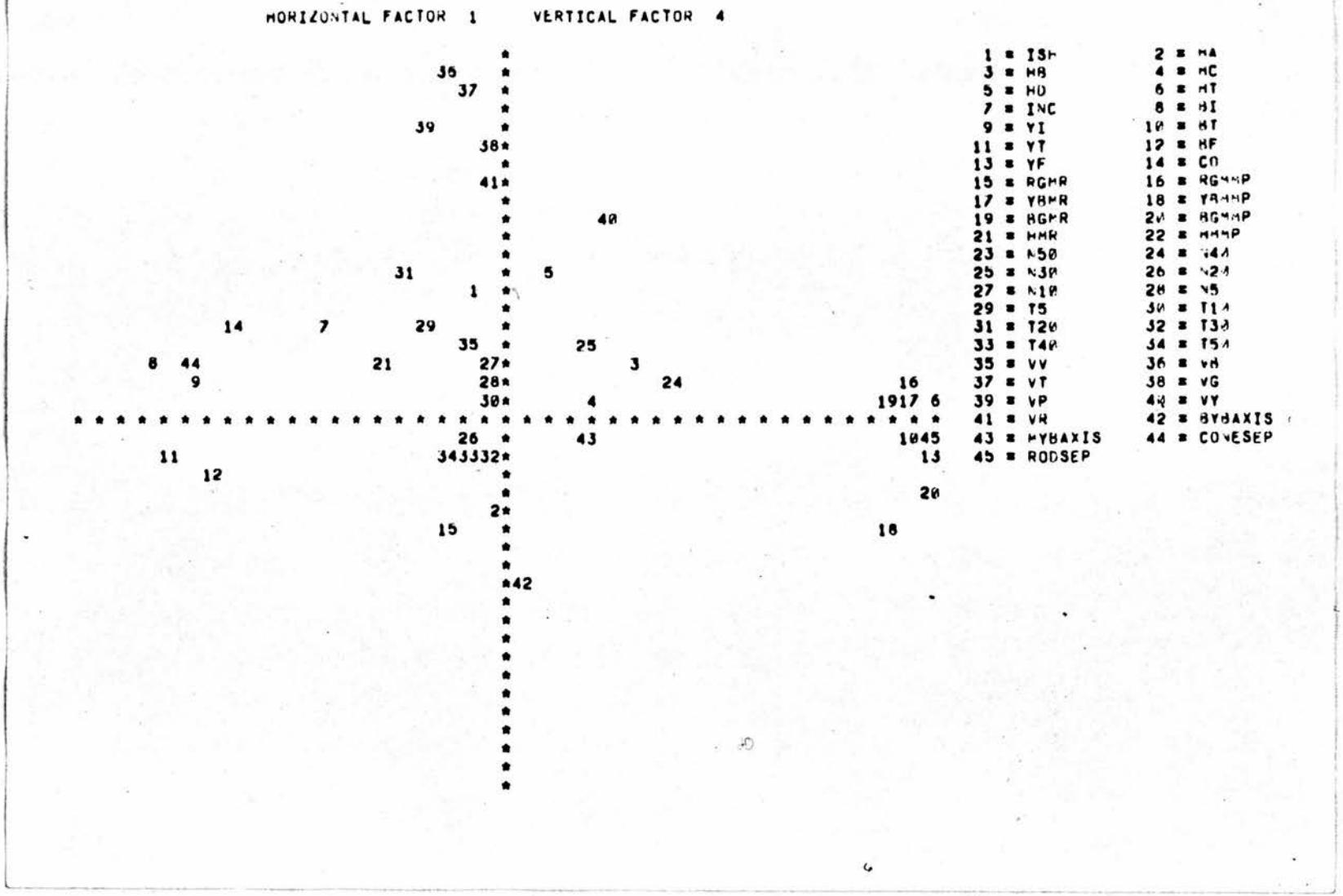

HORIZONTAL FACTOR 1 VERTICAL FACTOR 4
1 = ISH
2 = MA
3 = MB
4 = MC
5 = MD
6 = MT
7 = INC
8 = BI
9 = YI
10 = BT
11 = YT
12 = MF
13 = YF
14 = CO
15 = RGMR
16 = RGMMP
17 = YBMR
18 = YBMMP
19 = BGMR
20 = BGMMP
21 = MMR
22 = MMMP
23 = N50
24 = N40
25 = N30
26 = N20
27 = N10
28 = N5
29 = T5
30 = T10
31 = T20
32 = T30
33 = T40
34 = T50
35 = VV
36 = VB
37 = VT
38 = VG
39 = VP
40 = VY
41 = VR
42 = BYBAXIS
43 = MYBAXIS
44 = CONESEP
45 = RODSEP

Figure 109

although its factor 2 loading is comparable with them. It appears, therefore, that factor 2 could be identified with the static perimetric test situation as several thresholds load highly on this factor. Note also that there is no correlation between the dark adapted rod thresholds (variable 12) and the perimetry thresholds, suggesting that the bowl luminance has succeeded in eliminating rod influence in the peripheral retina. Furthermore, whatever is measured by the retinal threshold gradients cannot be linked with what is measured by the anomaloscope, as two orthogonal clusters represent the measures on the two tests. In other words it is possible that the foveal colour vision mechanisms are distinct from the peripheral cone increment threshold mechanisms.

Consider next Fig. 109 in which factor 1 is again plotted horizontally with factor 4 vertically. The distinctive cluster on factor 1 (i.e. variables 16, 19, 17, 6, 10, 13, 45, 20, 18) is again present. An addition to the cluster is the total 100 hue score variable 6. Factor 4 has a new set of variables loading highly on it (i.e. variables 36, 37, 39, 38, 41). These represent five of the wavelengths at which the flicker photometric measures were taken for determination of $V\lambda$. The other two wavelengths are represented by variables 40 and 35. Variable 40 has a high loading on factor 4 but a moderate loading on/

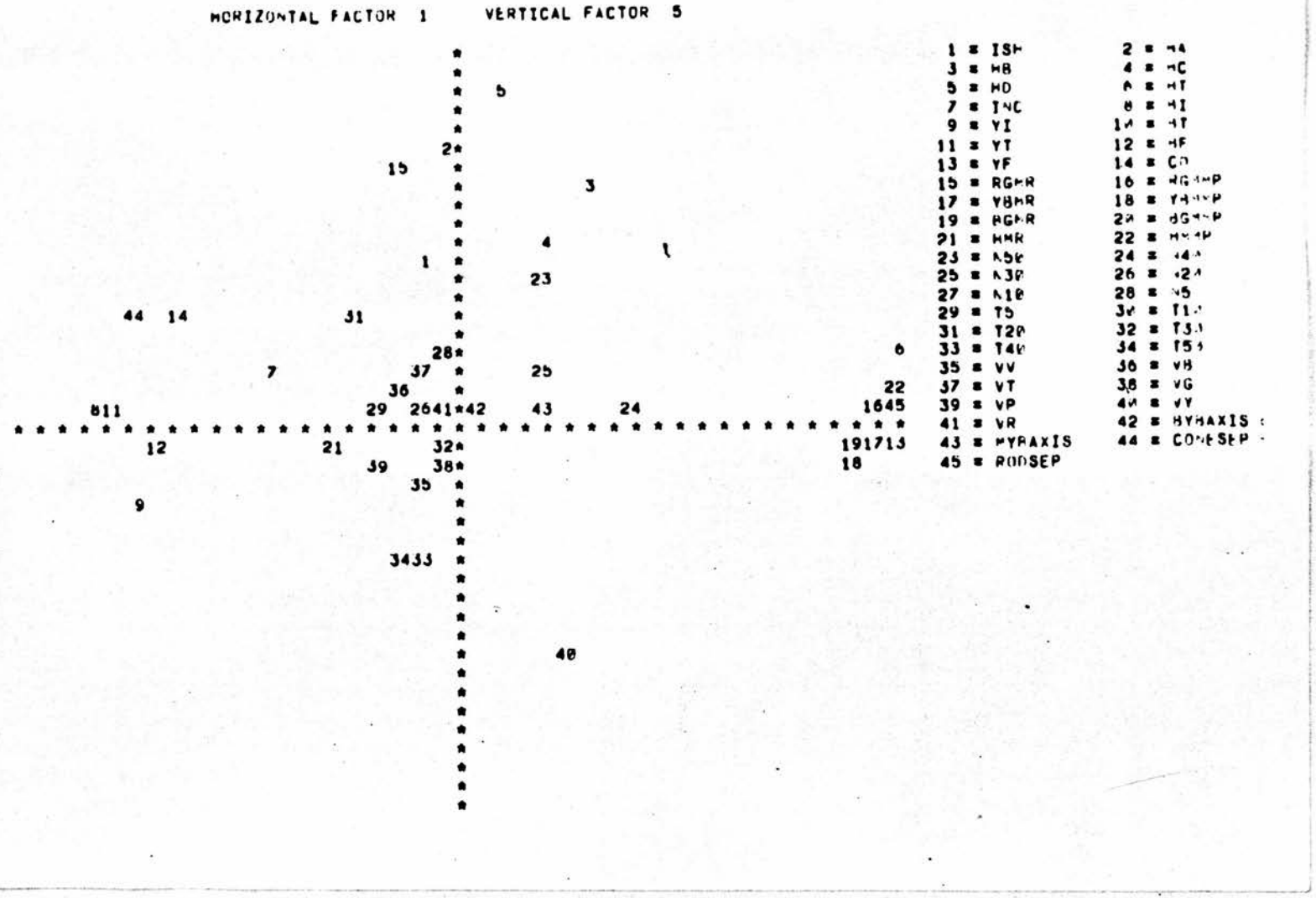

HORIZONTAL FACTOR 1
VERTICAL FACTOR 5
1 = ISH
2 = HA
3 = HB
4 = HC
5 = HD
6 = HE
7 = INC
8 = HI
9 = YI
10 = HT
11 = YT
12 = HF
13 = YF
14 = CD
15 = RGHR
16 = RGHP
17 = YBHR
18 = YBHP
19 = BGHR
20 = BGHP
21 = HHR
22 = HHP
23 = N50
24 = N40
25 = N30
26 = N20
27 = N10
28 = N5
29 = T5
30 = T10
31 = T20
32 = T30
33 = T40
34 = T50
35 = VV
36 = VB
37 = VT
38 = VG
39 = VP
40 = VV
41 = VR
42 = HYBAXIS
43 = HYRAXIS
44 = CONSEP
45 = RODSEP

Figure 110

on factor 1 which removes it from the cluster. On the other hand variable 35 (the violet measurement) is near the origin of the axes, and appears to be a different measure from the others. Therefore, with the exception of the violet measure, factor 4 can be identified with the photopic luminosity curve.

The photopic luminosity variables form a cluster which is orthogonal to the anomaloscope cluster, and therefore is a measure of a different source variable. It is perhaps surprising that the anomaloscope measure of colour discrimination in the blue does not correlate with the flicker sensitivity at the short wavelengths. It appears that the way in which the data is collected is very important in the association of the variables. Although there are several variables within tests which are independent (e.g. the red/green and blue/green equations in the Pickford anomaloscope), it is the tests which tend to determine the factors, rather than variables across different tests. This evidence strongly supports the notion of operational definitions in visual function testing, and furthermore supports the use of a test battery.

In Fig.110 factor 5 is plotted vertically against factor 1 horizontally. Note factors 15, 2, 5 and 1. These are measures of red/green sensitivity (variables 2 and 5 represent the first and the last of the 100 hue boxes which require discrimination among reds, variable/

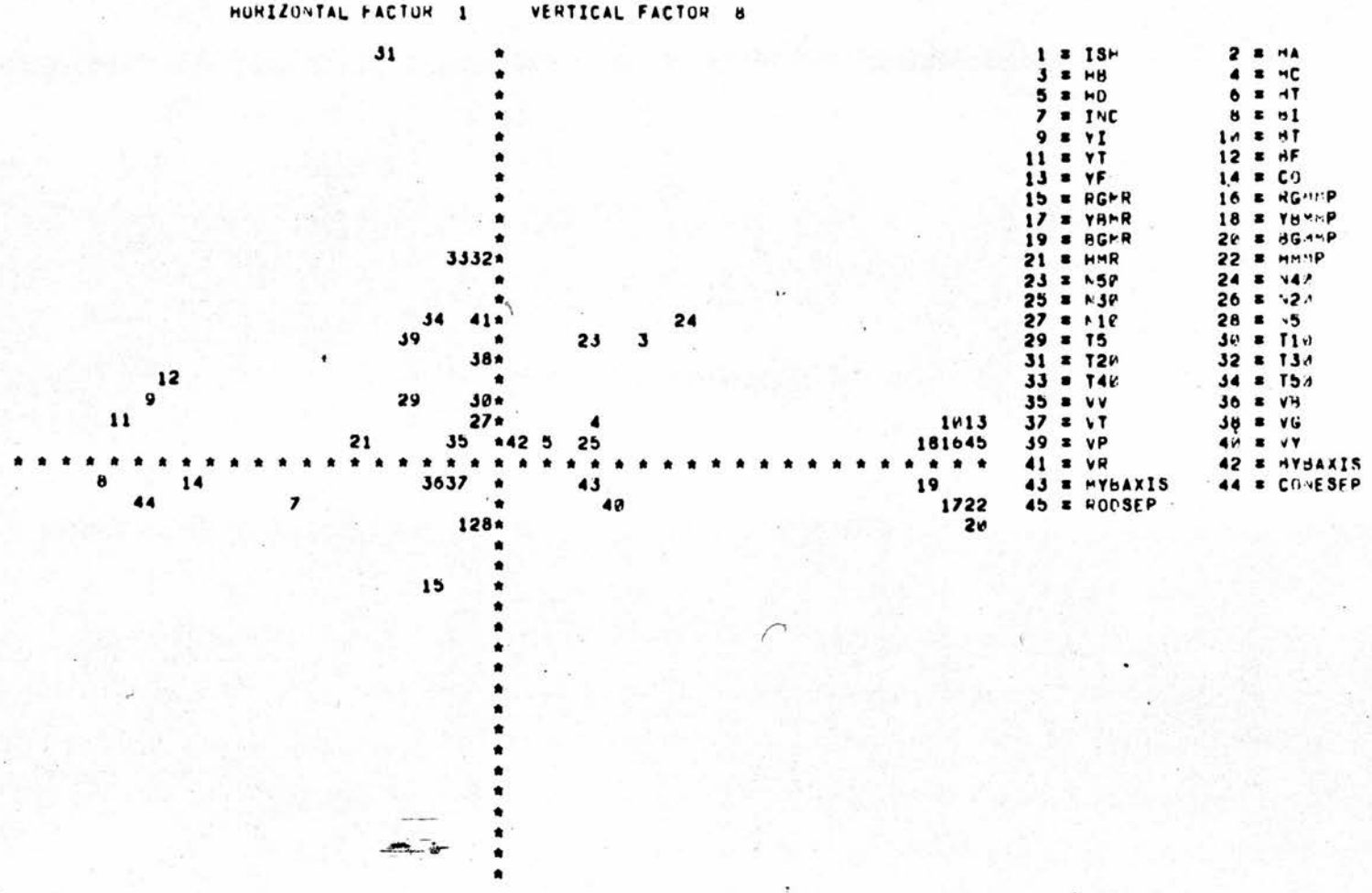

HORIZONTAL FACTOR 1 VERTICAL FACTOR 8
1 = ISH
2 = HA
3 = HB
4 = HC
5 = HD
6 = HT
7 = INC
8 = B1
9 = YI
10 = BT
11 = YT
12 = BF
13 = YF
14 = CO
15 = RGHR
16 = RGHSP
17 = YBHR
18 = YBHSP
19 = BGHR
20 = BGHSP
21 = HHR
22 = HHSP
23 = N5P
24 = N4P
25 = N3P
26 = N2P
27 = N1P
28 = N5
29 = T5
30 = T1N
31 = T2N
32 = T3N
33 = T4N
34 = T5N
35 = VV
36 = VB
37 = VT
38 = VG
39 = VP
40 = VY
41 = VR
42 = HYBAXIS
43 = HYBAXIS
44 = CONESEP
45 = RODSEP

Figure 111

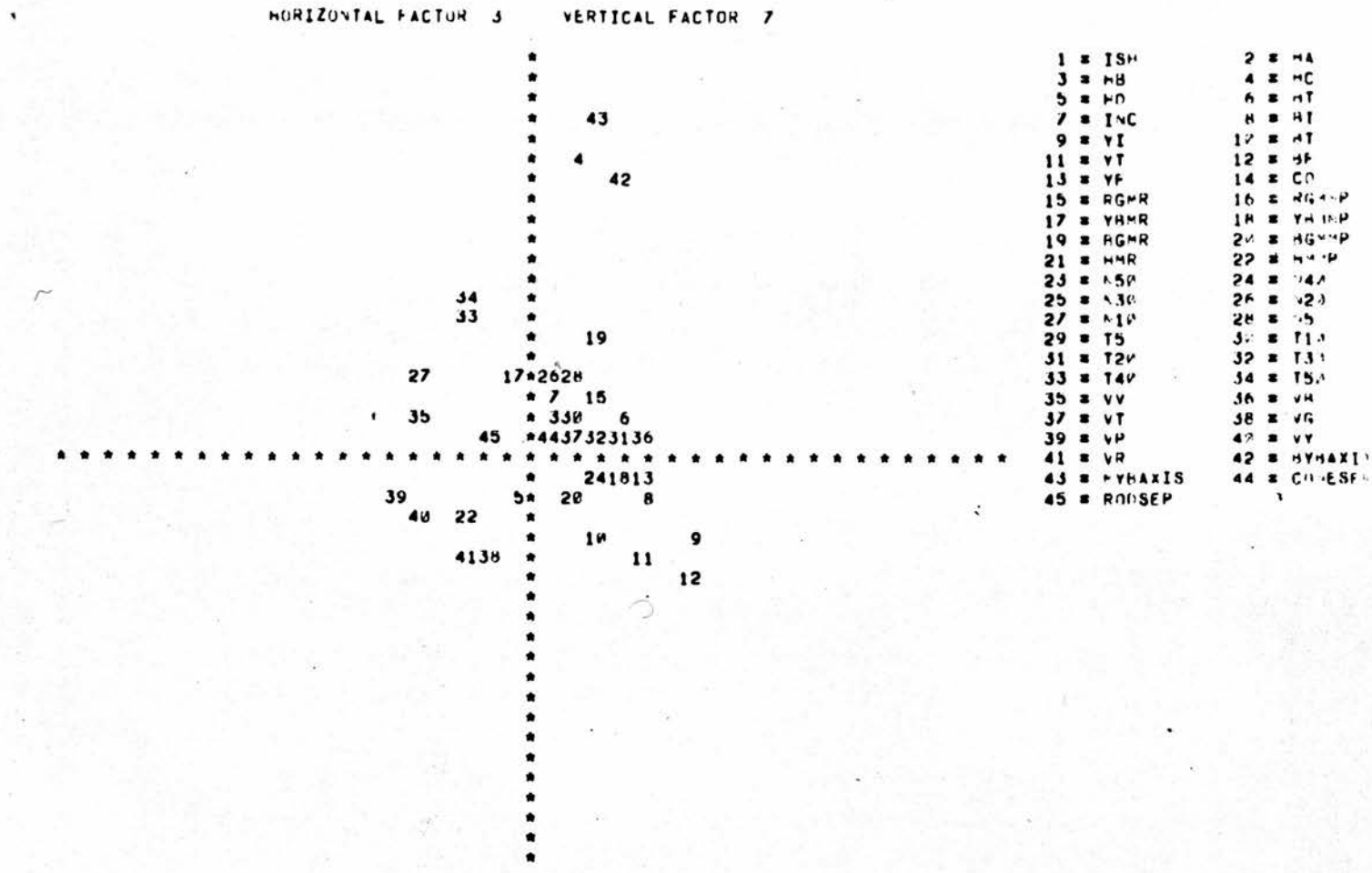

HORIZONTAL FACTOR 3
VERTICAL FACTOR 7
1 = ISH
2 = HA
3 = HB
4 = HC
5 = HD
6 = HT
7 = INC
8 = HI
9 = VI
10 = HT
11 = VT
12 = HF
13 = VF
14 = CO
15 = RGHR
16 = RG
17 = YBHR
18 = YB
19 = RGHR
20 = RG
21 = HHR
22 = HH
23 = V5R
24 = V4R
25 = V3R
26 = V2R
27 = V1R
28 = V5
29 = T5
30 = T1
31 = T2R
32 = T3
33 = T4R
34 = T5R
35 = VV
36 = VR
37 = VT
38 = VG
39 = VP
40 = VY
41 = VR
42 = HYBAXIS
43 = HYBAXIS
44 = CORESP
45 = RODSEP
VARIABLE(S) DELETED BECAUSE CORRESPONDING FACTOR MATRIX COMPONENTS HAVE ABSOLUTE VALUE GT 1.0

Figure 112

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variable 15 is the RGMR, and variable 1 is the Ishihara). The possibility of errors due to the skewness of Ishihara score has been mentioned above, but it is nevertheless interesting that in factor analysis this test is aligned with other red/green discrimination measures. Once again the blue/green measures lie orthogonal to factor 5. Note also that the cluster loaded negatively on factor 1 in Fig.108 is now split into two groups of variables 44 and 14, and variables 8, 9, 11, 12. This latter group represents absolute thresholds in dark adaptation while the variable closely associated with the cross-over time is cone separation. The uniqueness of the static perimetric threshold measurement adjacent to the blind spot is shown clearly in Fig. 111. Here variable 31, which represents the threshold at 20°T is highly loaded on factor 8 and not associated with other measures.

The main features of the analysis are shown in the early factor extractions, but nevertheless there are interesting points in the comparison of later factors. For instance in Fig.112 variables 4, 43, 42 form a cluster. Variables 42 and 43 are computed variables from raw data (See Table XXI). However, variable 4 is the 100 hue score for the blue/green caps around cap 45. This is the area in which the test is most difficult because the j.n.d. steps are smaller than elsewhere. The correlation between the caps centred/

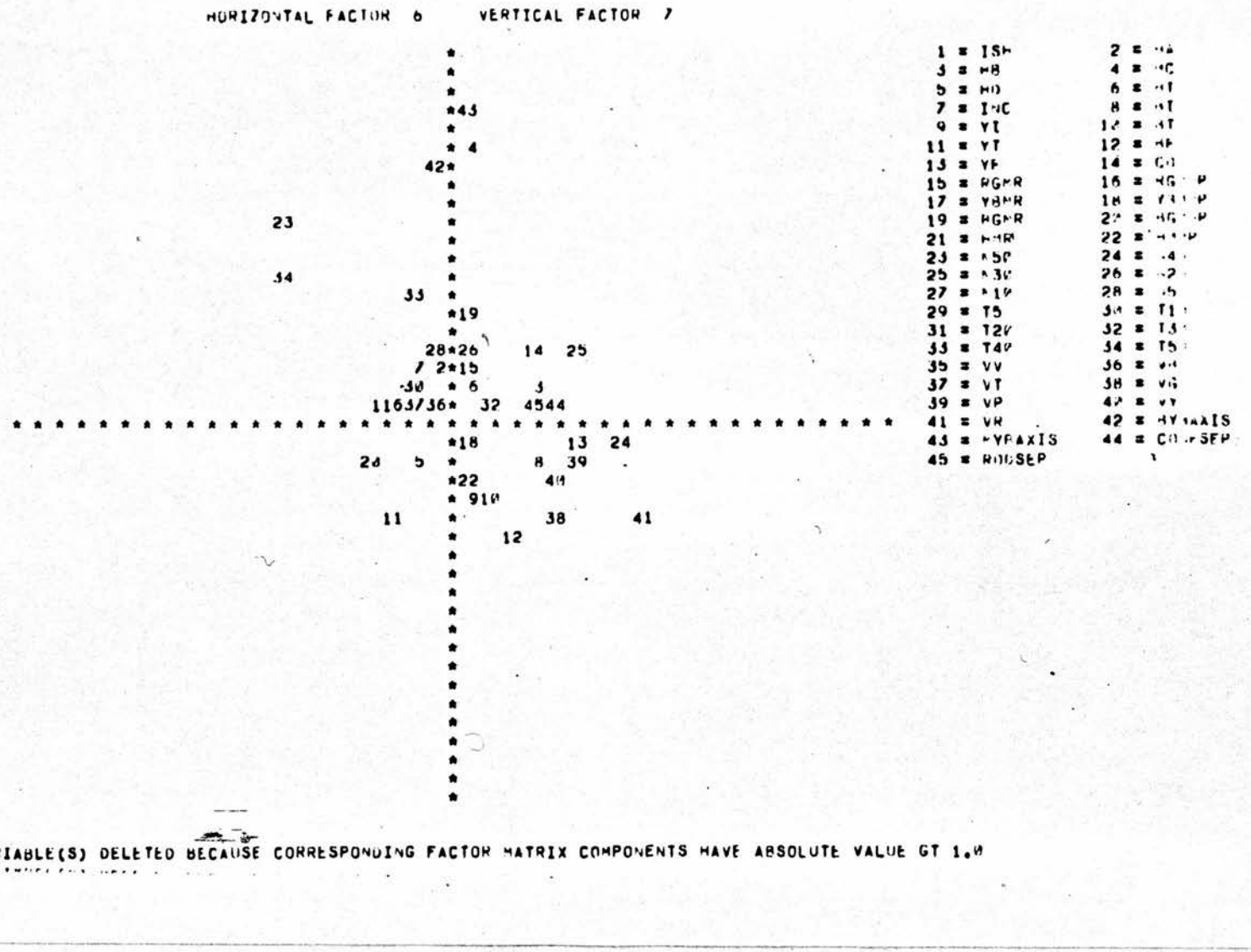

HORIZONTAL FACTOR 6 VERTICAL FACTOR 7
1 = ISH
3 = HB
5 = HD
7 = INC
9 = YI
11 = YT
13 = YP
15 = RGMR
17 = YBMR
19 = BGMR
21 = HMR
23 = A5P
25 = A3P
27 = A1P
29 = T5
31 = T2P
33 = T4P
35 = VV
37 = VT
39 = VP
41 = VR
43 = HYPAXIS
45 = RDCSEP
2 = HA
4 = HC
6 = HT
8 = HT
10 = AT
12 = HP
14 = GD
16 = HG P
18 = YA P
20 = HG P
22 = H P
24 = A4
26 = A2
28 = A
30 = T1
32 = T3
34 = T5
36 = W
38 = VG
40 = VY
42 = HYPAXIS
44 = COLRSEP
VARIABLE(S) DELETED BECAUSE CORRESPONDING FACTOR MATRIX COMPONENTS HAVE ABSOLUTE VALUE GT 1.0

Figure 113

centred on cap 45 and the rest of the test caps is low, resulting in the isolation of these cap scores on variable 7. Again in Fig. 113 variables 23 and 34 appear together. These represent the two extreme peripheral readings in static perimetry suggesting that measures at 50° temporal and 50° nasal are correlated.

Physiological Implications of Factor 1 loadings

One of the striking features of this analysis is the positive and negative loading of variables on factor 1. In particular it is the link between the cross-over time and the sensitivity to blue, as measured by mid-matching point shifts, that is of interest.

Possible links between blue vision and the rod receptors have been stressed on many past occasions. In fact it has been suggested that the rods are the blue receptors (WILLMER, 1961). Points in favour of this suggestion are:-

1.) the absence of rods in the fovea, and foveal small field tritanopia (See page 92).
2.) poor visual acuity for both rods and blue receptors (CLARKE, 1967).
3.) the periphery, where rods predominate, is more sensitive to blue than the fovea (WEALE, 1953).
4.) spatial integration of the blue receptors and the rods is similar (STILES, 1949).
5.) both the blue receptors and the rods produce/

produce a low sensation of luminosity.

Furthermore a blue colour is elicited by both.

6.) night blind patients are often tritanopic (RIDDELL, 1940).

7.) a'rod monochromat' may have blue cones (BLACKWELL and BLACKWELL, 1961).

Points against the suggestion are:-

1.) The Stiles-Crawford effect is shown by all cones, including blue ones, but not by rods.

2.) The difference in absorption curves for blue receptors and rods.

It is noticeable that even if the rods are not the blue receptors there remain several close similarities between them. A recent hypothesis (TREZONA, 1970) goes some way to reconciling the similarities and differences. Trezona suggests that the points against are associated with the receptor itself, but that the points for are associated with either neural pathways or sensation. His hypothesis suggests that the rods and blue receptors are separate receptors but share a common pathway. This sharing enables cones to inhibit the rods so that rods cut out at cone thresholds. Colour matching data reported by Trezona is given in support of this idea. Furthermore evidence that it is particularly blue cone inhibition is given by CLARKE, (1960) and BLACKWELL and BLACKWELL, (1961).

Let us consider the present findings in the light/

light of this hypothesis. The cross-over time represents the point at which rods take over function from cones. Up to this time the cones have been responsible for visual function. If rods and blue cones share the same pathway, then it is reasonable to suppose that the blue cones have inhibited rod action up to the cross-over point. Suppose however that a deterioration in blue vision has taken place, as shown by the diabetic matching ranges and mid-matching points. It is feasible that in this situation the strength of the inhibiting effect is reduced. Consequently rods would take over function at an earlier time after preadaptation than they would otherwise do. The result would be a shift in the cross-over towards earlier transition times.

The strong negative correlation between the cross-over time and the mid-matching points is in just this direction. In other words where shifts in mid-matching point towards the blue occur, there is a significant tendency towards early cross-overs. The factor loadings indicate that these are opposite effects on the same factor. In addition, if it was cones in general that inhibited rods, the red/green matching range would also be expected to load on this factor. The relation between long-wave cones and rods has been postulated (McCANN and BENTON, 1969). However the factor analysis indicates that this does not happen, and that it is/

is particularly the tests involving blue vision which are related to early cross-over times. This evidence strongly supports the hypothesis of rod-blue receptor linkage, and reinforces the idea that the inhibition of rods is due to blue cones.

(iii) Conclusions

In the diabetic eye colour vision is shown to be affected. It is the blue/green discrimination which deteriorates most in diabetes and which is most closely associated with retinal state as shown by the discriminant function analysis. This finding is supported in a follow-up study in which Bayesian statistics are used to predict the likelihood of retinopathy developing in a 5 year period. This is successful using the duration of diabetes, and the blue/green matching range as predicting variables.

In addition to the blue/green deterioration there is evidence of significant changes on many visual function tests, including dark adaptation and static perimetry, in diabetics with no retinopathy. Factor analysis suggests that ten factors are necessary to account for the variance in the data. This compares with forty-five original measures of visual function. Rod function and cone functions load on orthogonal factors as shown by dark adapted final thresholds and static perimetric peripheral thresholds. Also red/green discrimination and blue/green discriminations load/

load on orthogonal factors as shown by the red/green, yellow/blue and blue/green matching ranges. This indicates a different underlying source of variance, and reinforces the idea that different mechanisms are responsible for these visual functions. Apart from these general findings there is a tendency for tests to load on factors, rather than for variables across tests to load on factors. This supports the idea of operational definitions of visual function and the use of a test battery.

Finally, there is a close association between losses in sensitivity to blue and early dark adaptation cross-over times. This supports the hypothesis of rod-blue cone linkage and suggests the inhibition of rod function by blue cones.

b.) GLAUCOMA

1. Introduction

This study was an attempt to apply the signal detection methodology to the detection of absolute and incremental thresholds in patients with chronic simple glaucoma. Measurements were carried out on the Goldmann Perimeter. No colour discrimination tests were given because of the length of time necessary to collect the basic threshold data. However, colour discrimination together with other visual function data in glaucoma, are briefly reviewed below./

below.

(i) Background

Several authors report normal colour vision in glaucoma patients (e.g. BARBELL, (1939) discovered only a minor colour defect, using the Ishihara and Stilling Plates, in 34 out of 102 glaucomatous eyes). Also Roenne and Traquair report that the colour isopters in perimetry do not show selective losses. On the other hand WESSELY (1927), PICKARD (1938) and SZMYT (1951) report selective losses for red targets. This is supported by ZARETSKAYA (1955) who reports a decreased electro-retinogram for red stimuli.

KOELLNER (1912) found a typical dyschromatopsia of the red/green axis which did not follow visual acuity changes. Similarly VERROY (1926) describes a shift in the Raleigh equation towards the green. Again yellow/blue dyschromatopsias have been reported in glaucoma by BULL (1883), SIMON (1905), BEAUVIEUX and DELORME (1913). Green and blue stimuli appeared mostly affected with only eventual losses to red stimuli. SCHMIDT (1954) reported yellow/blue defects on the Nagel anomaloscope which improved as the level of retinal illumination was increased.

Of the more recent studies, FRANCOIS, VERRIEST and DE ROUCK (1957), found a yellow/blue defect in congenital glaucoma. Also primary glaucomas were found to give rise to yellow/blue defects. In 34 eyes affected by/

by open angle glaucoma and 47 eyes affected by closed angle glaucoma, each group had 20% of eyes with normal colour discrimination, 40% with doubtful discrimination, 35% with yellow/blue type losses, and 5% with red/green type losses. The preponderance of yellow/blue defects was confirmed by BOZZONI, (1959) in 22 cases of chronic open angle glaucoma, where several patients showed tritan like profiles on the 100 hue test. Again ANDREZEN (1959) showed that colour vision was affected in 70% of glaucomatous eyes with particular losses in blue vision being evident in all types of glaucoma. DUBOIS-POULSEN and MAGIS, (1960) in a study of 80 glaucomatous eyes found yellow/blue losses which were similar to, but distinguishable from, tritanopic losses. COX, (1960) found yellow/blue defects in ten out of thirteen eyes. Only five of the ten were discernable on the 100 hue test. No difference was apparent between open angle and closed angle glaucoma.

Extensive studies by VERRIEST (1964) revealed the following results. In congenital glaucoma acquired dyschromatopsias of the yellow/blue axis were found with concomitant damage to the red/green axis. In a study of 53 eyes with primary closed angle glaucoma, 10% of eyes showed a yellow/blue axis. This appeared as a late defect and most eyes remained normal in colour vision. The Rayleigh equation was normal in all cases. In primary open angle glaucoma forty-four eyes were/

were studied. 75% per cent of cases showed yellow/blue defects with 33% discernable on the 100 hue test. Thus there was a greater proportion of defects in open angle than closed angle glaucoma. Verriest found the colour defect to be present when visual acuity was normal while the dichromatic stage was reached when the visual acuity was reduced to 0.6. The Rayleigh equation was sometimes shifted to the red but the photopic luminosity curve remained normal. In three cases of Von Graefe's disease Verriest found an acquired dyschromatopsia of the red/green axis (type II). He suggested that the condition was distinguishable from primary open angle glaucoma by colour vision tests as well as by blood pressure tests.

Recently LAKOWSKI, BRYETT, DRANCE, (1972) used colour vision tests on ocular hypertensives with open angles, normal acuity, and full fields, and found colour vision losses greater than those in equivalent age control groups. Half the patients had losses on the yellow/blue and green/blue equations with additional shifts in mid-matching point towards the blue. Other patients had matching ranges across the equation characteristic of dichromatism. Most subjects showed a concomitant shift in the red/green equation towards the green. Wavelength discrimination studies by GRUETZNER and SCHLEICHER, (1972) showed losses in glaucoma at the short wavelengths similar to tritan like defects./

defects. GRUETZNER raises the question of why there are tritan colour defects and not deutan colour defects, as in other conditions which affect the 'third neuron'. He suggests that colour defects are correlated with the extent of field loss. As short wavelength receptors may be linked with rods (see rod/blue cone link in diabetes, page 320),paracentral scotomas may be affecting blue vision.

Dark adaptation studies in glaucoma have indicated losses in the final rod thresholds MANDELBAUM (1941), JAYLE and OURGAUD, (1950). The final thresholds in addition to being raised, were reached at a later stage in the adaptational process. OURGAUD and ETIENNE (1961) using a small target at 15° excentricity showed abnormal dark adaptation curves. ZUEGE and DRANCE, (1967) also studied dark adaptation at 15° excentricity and at 30° excentricity, and compared the dark adapted final thresholds at both locations. Their findings suggested predominantly rod impairment. The thresholds during dark adaptation of glaucomatous eyes became greater than the 95th percentile point for normals after the 10th minute into the dark adaptation process. The final 30th minute thresholds showed the greatest difference from normal. The ratio of the final threshold at 15° excentricity to that at 30° excentricity was calculated. This ratio was less than unity (i.e. the thresholds were lower at 15° than 30°) in most/

most normal eyes, but greater than unity in most glaucomatous eyes. In an ocular hypertensive group with normal discs and full fields, the ratio was abnormal in 25% of the group, although the dark adapted thresholds had been normal at 15° excentricity. The ratio was also abnormal in cases where static or kinetic fields had been normal at higher background luminances. Thus, the ratio may be an indication of subsequent visual field defects.

One of the striking features of this study and the study of ZUEGE and DRANCE (1967) on dark adaptation in normal eyes, is the size of the confidence interval in normal vision. Two standard deviations above and below the mean result in a span of 2 log units on the threshold scale. In other words the range of normal vision can include thresholds which differ in their sensitivity to light by a factor of 100. It has been argued in Section II that the sensitivity of the measurement is related to the span of normal variation. Furthermore, any technique which reduces or eliminates an error component will improve sensitivity by reducing this span. Thus to eliminate the effects of response bias is to increase sensitivity. The reason why ZUEGE and DRANCE found the ratio of sensitivity at 15° and at 30° excentricity to be a useful measure, was presumably because a high correlation existed between dark adapted final thresholds at 15° and 30°. Consequently, although/

although the absolute levels at the two points varied over a wide range, the confidence limits of a regression line between them were narrower. Thus there may be nothing particularly significant about thresholds per se at either 15° or 30°. Any retinal location whose thresholds correlated with those at a second point would suffice.

In an attempt to explore these possibilities and to reduce the error in the measurement, the present study was devised. Although colour vision tests were not given to the patients, an independent measure of rod and cone sensitivity was included in the measurement.

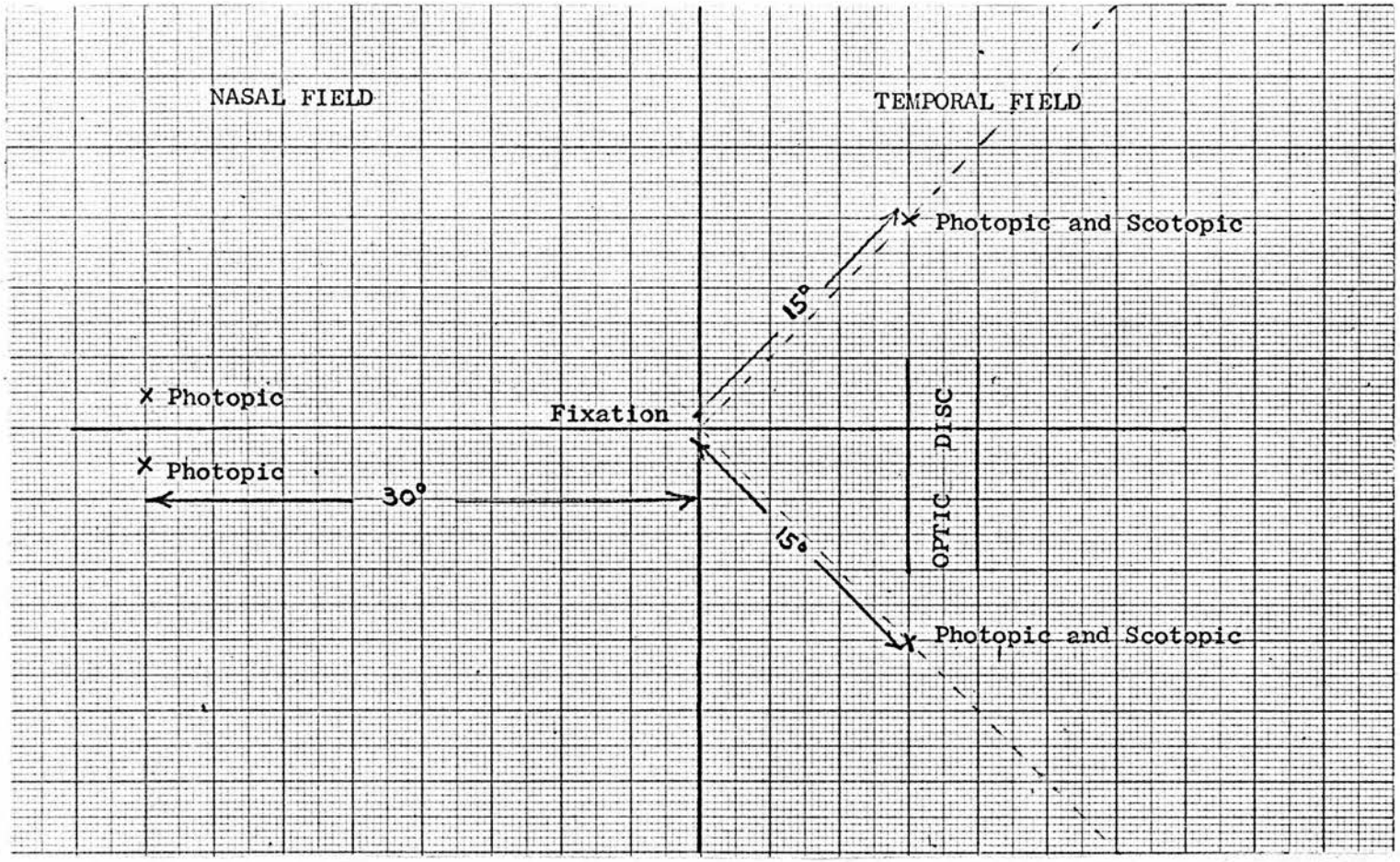
(ii) Present Study

Method

The experimental procedure consisted in determining the absolute thresholds above and below the blind spot at 15° excentricity against a totally dark Goldmann bowl, and against the high luminance Goldmann bowl. Patients were dark adapted for 30 minutes before the dark adapted measurements were taken. The incremental thresholds against the high luminance Goldmann bowl were determined after five minutes adaptation to the high luminance. In addition, thresholds against the light bowl were determined at 30° excentricity in the nasal field. Two measurements were taken at this excentricity; one above the horizontal meridian and one below the horizontal meridian. /

Figure 114

Retinal Locations for threshold determinations under Photopic and Scotopic Conditions



meridian.

Locations at which testing was carried out are shown in Fig. 114 . This enabled rod thresholds and cone thresholds to be determined at points adjacent to the blind spot, and cone thresholds to be determined in the nasal field above and below the horizontal meridian. (For assumptions that cone thresholds are measured in the peripheral retina, see page 238). Thresholds were measured by the normal one-way method of limits and by a temporal forced choice method. This latter method was carried out as follows.

A fixed intensity of the target luminance was chosen corresponding to the threshold value calculated by the method of limits. Two time intervals, each of two seconds and separated by an interval of one second, were defined by a buzzer. The signal or light stimulus presentation, always occurred in one of the two time intervals. Twenty such pairs of intervals completed one trial run at one chosen value of stimulus intensity. The time interval containing the signal was randomly allocated over the 20 trials with the following constraint. Once one time interval was fixed, the succeeding one occupied the alternative interval. This ensured that over the twenty intervals, half the signals occurred in the first of the two intervals, and half occurred in the second of the two intervals. The patients were informed that the signals were evenly divided over/

over the two intervals. (This is important because it helps to minimise bias due to guessing and to maintain a constant response criterion within different individuals).

Depending on the results obtained from the first set of 20 measurements a second stimulus intensity was selected and the procedure repeated.

The experimental data obtained was coded as follows:

DAI1 - Dark bowl; Above blind spot; threshold intensity I1

DAF1 - " " " ; frequency of hits at intensity I1

DAI2 - " " " ; intensity I2

DAF2 - " " " ; frequency of hits at intensity I2

DBI3 - Dark bowl; Below blind spot; threshold intensity I3

DBF3 - " " " ; frequency of hits at I3

DBI4 - " " " ; intensity I4

DBF4 - " " " ; frequency of hits at I4

LA15 -Light bowl; Above blind spot; threshold frequency I5

LAF5 - " " " ; frequency of hits at I5

LAI6 - " " " ; intensity I6

LAF6 - " " " ; frequency of hits at I6

LB17 -Light bowl; Below blind spot; threshold intensity I7

LBF7 - " " " ; frequency of hits at I7

LB18 - " " " ; intensity I8

LBF8 - " " " ; frequency of hits at I8

NAI9 -Light bowl; Nasal field 30° Above horizontal ; threshold intensity I9/

;

; threshold intensity I9

NBI10 - Light bowl; Nasal field 30° Below horizontal

; threshold intensity I10

DAI1, DBI3, LAI5, LBI7, NAI9, NBI10 were normal threshold values obtained by the method of limits. With the exception of the last two values, these were the intensities used for the first series of forced choice runs at the appropriate retinal locations. The corresponding frequency of hits for each intensity value was given by DAF1, DBF3, LAF5, LBF7 respectively.

A second intensity value was selected at each retinal position, depending on the frequency of hits at the first intensity setting. The second intensity values were DAI2, DBI4, LAI6, LBI8 with corresponding hit frequencies of DAF2, DBF4, LAF6, LBF8 respectively.

In addition to these threshold values the age, pupil diameter, and ocular tension were recorded. The group of patients had all attended a chronic simple glaucoma clinic, and could be considered as a sample of potential glaucoma patients with no clinical abnormalities. They were made up of three subgroups:-

(i) The first consisted of those patients with suspected glaucoma on the basis of ophthalmoscopically suspect disc or raised tensions. All had clinically normal fields and good visual acuity.

(ii) The second group consisted of those patients/

patients with established glaucoma in one eye but no symptoms or abnormalities in the other eye. The 'normal' eye was tested.

(iii) Thirdly, a small group of glaucoma relatives were tested who had no clinical abnormalities.

In addition to an investigation of glaucoma thresholds, the method employed enabled an investigation of the slope of the psychometric function at photopic and scotopic levels to be carried out. This information is presented first, followed by an analysis of the glaucoma population.

2. General Features

Findings which are applicable to the whole group provide an indication of absolute threshold levels and implications for threshold determinations in static perimetry.

(i) The Psychometric Function

Under scotopic test conditions the mean threshold level above the blind spot was 21.00; (σ = 4.37) and below the blind spot was 18.6; (σ = 4.10). As lower numbers indicate less target light intensity at threshold the results confirm the findings of DRANCE (1967) that sensitivity adjacent to and below the blind spot, is greater than sensitivity adjacent to and above the blind spot.

The 57 threshold determinations in scotopic conditions by the method of limits, produced 57 x 20/

57 x 20 = 1,140 forced choice responses. (The method of limits 'threshold value' was used as the first target intensity setting in the forced choice situation). The calculated mean detection rate of the normal perimetric threshold was found to be 93%. In other words, the threshold value obtained by the one-way method of limits gave 93% of 1,140 correct answers in the forced choice situation. Furthermore, of particular concern was the fact that 49% of the patients had set the response criterion so high, that they obtained 100% correct answers in the detection situation. Thus the recorded threshold was outside the true threshold range. The range of the response frequencies corresponding to the method of limits threshold was 60 to 100%. It is evident that observers use widely varying response criteria in a method of limits threshold measurement. It seemed important therefore, to investigate the relationship between the threshold intensity values and the response frequencies (i.e. the psychometric function) under scotopic conditions. In the experimental design the threshold intensity value was changed after the first set of 20 paired intervals. The change was frequently 0.2 log units. If 100% correct detection was obtained on the first trial run the intensity would be reduced by this amount for the second run. If 50% or less correct detection was obtained on the first trial run the intensity would be reduced by this amount/

amount for the second run.

The slope of the psychometric function is given by the mean values of:-

$$\frac{DAF1 - DAF2}{DAI1 - DAI2} \quad \text{and} \quad \frac{DBF3 - DBF4}{DBI3 - DBI4}$$

In obtaining this expression, all values of intensity level with a corresponding hit rate of 100% or 50% chance level were not included in the calcualtion. (This is necessary to prevent artificial bias of the intensity/frequency relation).

The mean value of the above expression was 2.3. Thus each 0.1 log unit of intensity change produced on average, a frequency change of 2.3 or 11.5% change in the probability of detection. Consequently, in the threshold range from chance to 100% probability of detection, 0.6 log units of light intensity are necessary under scotopic conditions to cover this range in the population. This compares with a value of 0.4 log units with two trained observers (GREVE, 1972).

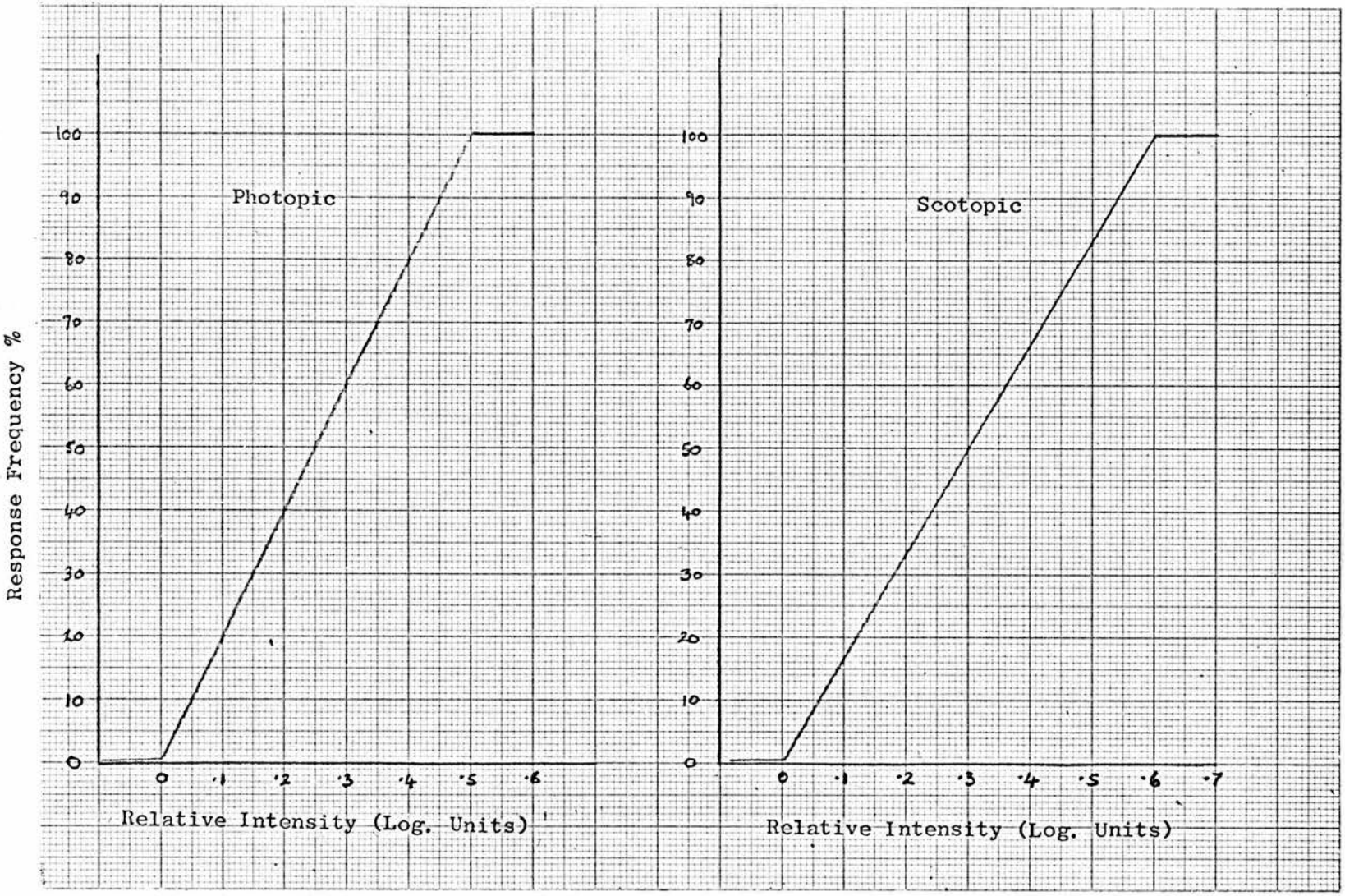
In a similar way the psychometric function can be plotted for photopic conditions using the mean value of:-

$$\frac{LAF5 - LAF6}{LAI5 - LAI6} \quad \text{and} \quad \frac{LBF7 - LBF8}{LBI7 - LBI8}$$

The calculated mean value was 3.0 so that under photopic conditions each 0.1 log unit of light intensity/

Figure 115

The Photopic and Scotopic Psychometric Function



intensity produced on average a frequency change of 3.0 or 15% change in the probability of detection. Consequently in the threshold range from chance to 100% probability of detection, 0.5 log units of light intensity are necessary under photopic conditions to cover this range in the population. The graphs of the scotopic and photopic psychometric functions are plotted in Fig. 115 The steeper slope of the photopic function shows that there is a greater variation in scotopic than photopic thresholds.

(ii) Group Results

The method of limits threshold values may now be corrected to obtain equivalent detection rates for each individual based on the psychometric function for either scotopic or photopic conditions. Under scotopic conditions this can be achieved by calculating either for

threshold DAI1: $D = DAI1 + \frac{(20 - DAF1)}{2.3}$

or for DAI2: $D = DAI2 + \frac{(20 - DAF2)}{2.3}$

The choice of either DAI1 or DAI2 depends upon the associated frequency of correct answers being less than 20. The effect of this calculation on the detection rate is to move the threshold intensity values below the group mean nearer to the mean, but the threshold intensity values above the mean farther from the mean. The amount of movement depends on the difference/

difference between the correct response frequency and certainty. Calculations showed that the mean threshold for the group was not affected by the transformation (it equalled:- 21.00 using method of limits and 20.87 using the forced choice method)

However, the variance of the measurements was changed from 19.1 to 12.4. (Note that this group variance change is not accountable by simply increasing the number of measurements (N) so that the variance in the measurement is reduced as an inverse function of $\sqrt{N}$. It is the intra individual variation which is reduced by the number of measurements, and hence by the ratio $\sqrt{40/3}$ or a factor of 3.5, as 40 measurements determined the forced choice threshold and three measurements the method of limits threshold. The inter group variation reflects the differences in detection ratios between individuals. The forced choice method provides a more genuine indication of this group variation. The method of limits provides a measure of group variation which also includes more intra individual variation and response criterion variation).

The forced choice method has reduced the variance in the threshold in all situations. Similar calculations for thresholds below the blind spot using either

$$D = DBI3 + \frac{(20 - DBF3)}{2.3}$$

or

$$D = DBI4 + \frac{(20 - DBF4)}{2.3}$$

resulted in a reduction of variance from/

T A B L E XXV

Means and Standard Deviations for Scotopic and Photopic Conditio

	Retinal Location			
	Scotopic		Photopic	
	15° above BS	15° below BS	15° above BS	15° below
Mean Threshold Method of Limits	21.0	18.6	25.2	24.3
Variance	19.1	16.8	14.9	13.9
Mean Threshold Forced Choice	20.87	18.7	27.0	25.8
Variance	12.4	10.5	8.5	6.7

from 16.8 to 10.5. Under photopic conditions the appropriate formula above the blind spot is either

$$D = LAI5 + \frac{(20 - LAF5)}{3.0}$$

or $$D = LAI6 + \frac{(20 - LAF6)}{3.0}$$

and below the blind spot is

either $$D = LBI7 + \frac{(20 - LBF7)}{3.0}$$

or $$D = LBI8 + \frac{(20 - LBF8)}{3.0}$$

The reductions in variance after the transformation were from 14.9 to 8.5 above the blind spot and from 13.9 to 6.7 below the blind spot.

In view of these findings there seems little question that the accuracy of the visual function test is greatly improved under the methodology of the forced choice procedure. The means and variance reductions are given in Table XXV. The comparison between the variances under photopic and scotopic conditions, gave further support to the change in slope of the psychometric function at the two adaptation levels. The variances associated with the forced choice means can be said to represent genuine variability in detection rates of the total group.

(iii) Relationships between Variables

There are some interesting correlation coefficients/

coefficients between the variables over the total group. Firstly there was a significant positive correlation between age and the intra-ocular tension so that with increased age the tension increased. ($r = .38$; $p < .05$).

The mean age of the group was 59 years with a range from 38 to 75 years. The mean value of tension was 18.8 mm. with a range from 12 mm. to 23 mm. This finding is in accordance with DUKE-ELDER (Vol.XI, 1968) that in a normal eye there may be a slight rise in tension from 40 to 75 years.

Secondly, there were the expected correlations between age and the threshold level.

Under scotopic conditions			above the blind spot		($r = .506$ $p < .01$)
"	"	"	below	"	($r = .427$ $p < .01$)
"	photopic	"	above	"	($r = .315$ N.S.)
"	"	"	below	"	($r = .641$ $p < .01$)
"	"	"	in the nasal field		($r = .53$ $p < .01$)
					($r = .49$ $p < .01$)

In all cases, the older the individual, the lower the threshold. There seemed to be little relationship between tension and threshold levels. However, it was of interest that the relationship between the tension and the rod threshold above the blind spot was almost significant, while that between tension and the cone threshold at the same point was significant. Points below the blind spot showed no threshold relation with/

with tension.

The effect of pupil diameter on threshold values was shown by significant negative correlations in every case where rod thresholds were measured ($r = -.609$ $p < .01$ above the blind spot: $r = -.478$ $p < .01$ below the blind spot). However, there was no relation between pupil diameter and cone thresholds ($r = .02$, not significant above the blind spot: $r = -.10$, not significant below the blindspot). This clarified the finding of ASPINALL (1967) that there was no relationship between pupil diameter and peripheral thresholds at a luminance level of the standard Goldmann test condition. However, under scotopic conditions there was a strong negative relationship so that smaller pupil diameters resulted in higher thresholds.

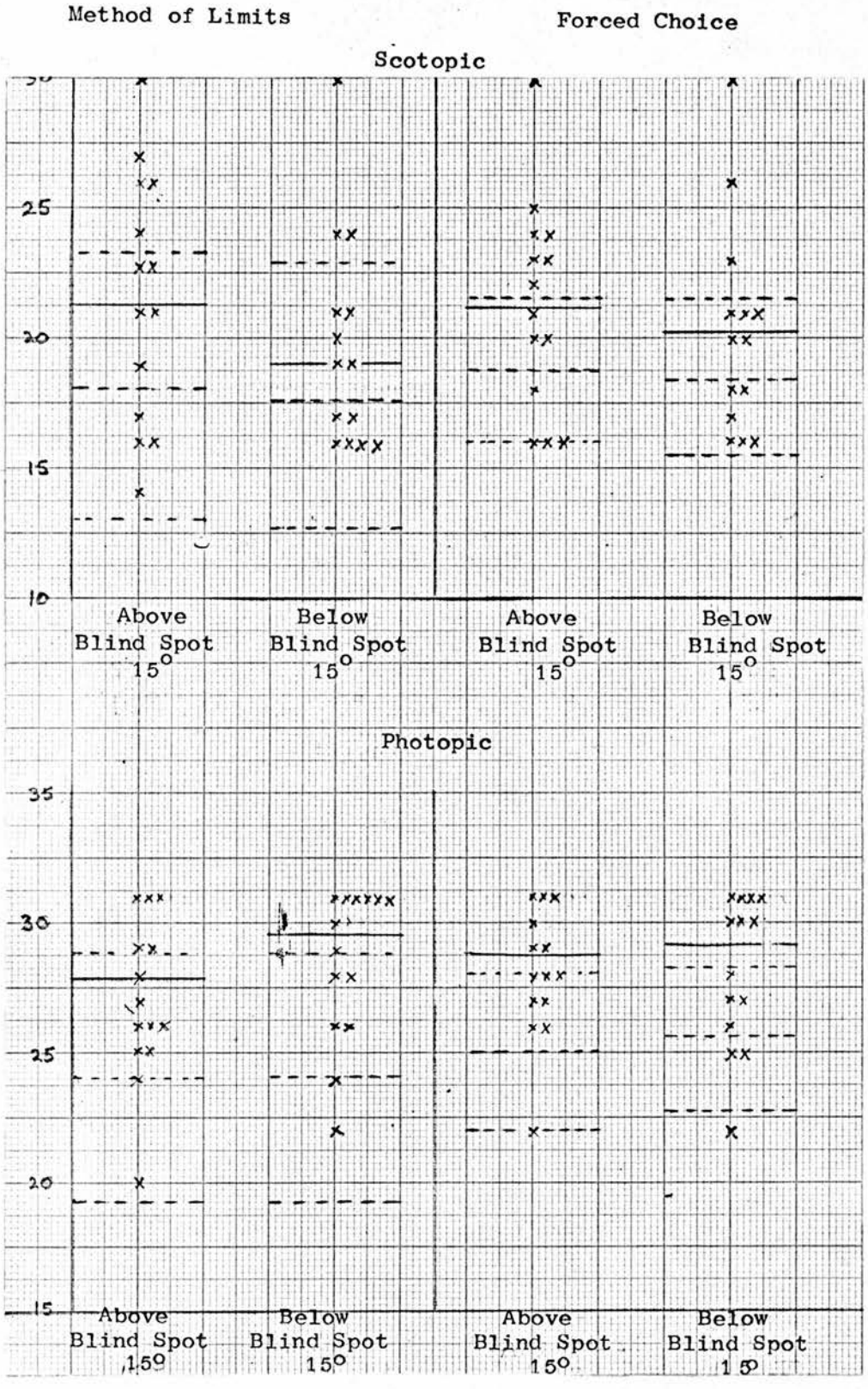
The correlation coefficient between scotopic threshold values above and below the blind spot was significant ($r = 0.57$ $p < .01$). If this finding is representative of the relationship between scotopic thresholds, so that scotopic thresholds correlate at different retinal points, this would explain why ZUEGE and DRANCE (1967) found the ratio of the final thresholds at 15° and 30° excentricity useful as it reduced the variability of absolute threshold measurements.

A comparison of scotopic and photopic thresholds at the same retinal location indicated the presence of small positive correlations ($r = .34$ $p < .05$). Thus/

Thus the position of the cone threshold was related to the position of the rod threshold. The retinal function in peripheral regions has been shown to be characteristic of cones at the high luminance levels of the bowl. Similarly, at zero luminance the function has been shown to be characteristic of rods (See page 242). If two independent mechanisms are responsible for the threshold value at the two luminance levels, there would by definition be no correlation. Two explanations seem possible. The first is that the scotopic and photopic systems are not independent, even when the luminance levels are sufficiently far removed for the full Purkinjie effect to take place. The second is that in this sample of potential glaucoma patients, deterioration has occurred in both cone and rod systems. In this situation both cone thresholds and rod thresholds would be related to a third common factor which causes deterioration, and so a positive correlation would exist between rod and cone thresholds. Both explanations may apply in this particular group. The relationship between rod and cone function is extremely complex. In both normal and diabetic dark adaptation curves there is a correlation between the threshold at four minutes (cone), and that at 20 minutes (rod). Again, a relation between rods and 'red cones' has been postulated (McCANN and BENTON, 1969) in addition to the rod/blue cone link proposed in the last/

Figure 116

Thresholds by the method of limits and the method of forced choice under Scotopic and Photopic Conditions



last Section (page 320). The question of deterioration in both systems is treated for each subgroup below.

3. Subgroup 1

The group consisted of those patients with good Snellen visual acuity and full fields. However for some reason they had initially attended the Hospital Out-Patient Department, and had subsequently been asked to periodically attend the glaucoma clinic because of ophthalmoscopically suspect discs or raised tensions (see page 331 for a description of the method.)

(i) Results

The mean age of 14 patients in the group was 59 years, and the mean value of tension was 19.7 mm. with a range from 15 mm. to 23 mm. The individual threshold values above and below the blind spot under scotopic and photopic conditions are plotted in Fig. 116. Values on the left refer to the method of limits thresholds and values on the right refer to the forced choice thresholds. The means and standard deviations of the group and of the normals are also plotted.

(ii) Discussion

Considering the point above the blind spot, the method of limits thresholds showed that five out of the 14 patients had thresholds beyond the normal population thresholds. The forced choice threshold indicated that 7 out of the 14 patients were beyond normal threshold limits. The greatest threshold change/

change between the methods was 0.3 log units. This occurred in three individuals in the group. The true (forced choice) threshold value was 0.3 log units lower than indicated by the method of limits in two cases, and higher by the same amount in the third case. This provided once more an indication of the range over which thresholds could fluctuate. Nevertheless, the normal static perimetric method had picked five out of the seven individuals indicated by the forced choice method as having abnormal thresholds and therefore, requiring observation. The change in classification between the two methods occurred in two individuals formerly classified as within normal limits, who now appeared just beyond the normal limits.

The thresholds below the blind spot indicated that three individuals were outside the normal limits by both methods, and also that it was the same three individuals in both cases. The true thresholds extended over a range of 0.7 log units at equal intervals. The normally measured thresholds extended over 0.6 log units with two individuals measured at the same threshold. Of the three individuals judged to be abnormal below the blind spot, two had abnormal thresholds above the blind spot. They were, therefore, included in the former group of 7 abnormals.

A total of eight individuals had abnormal thresholds values out of 14 tested under scotopic/

scotopic conditions. Of these eight, two had abnormal thresholds both above and below the blind spot; five had abnormal thresholds above the blind spot, and one had an abnormal threshold below the blind spot. In Fig. 116 the photopic results are plotted. Above the blind spot there were three individuals outwith normal limits, and two others on the borderline. The forced choice method placed 6 out of the 14 outwith normal limits. Below the blind spot there were 7 individuals placed outside normal limits by both methods.

These results are rather surprising as the early visual losses in glaucoma have been particularly associated with the rod system (ZUEGE and DRANCE, 1967). If it is assumed (as previously) that the forced choice method reveals the true threshold, the method of limits gave two wrong classifications. One individual judged to have a normal threshold had an abnormal one, and one individual judged to have an abnormal threshold had a normal one. Otherwise the same individuals were classified as normal or abnormal by the two methods. The photopic thresholds indicated that only five patients had normal thresholds. Of the remaining nine, five were abnormal both above and below the blind spot, three were abnormal below this point and one was abnormal above. (The grouping of abnormal thresholds in Fig. 116 is an artefact. The normal limit of photopic thresholds extends almost to the upper/

T A B L E XXVI

Pattern of Individual Thresholds

(+ normal - abnormal)

	Scotopic		Photopic	
N	Above	Below	Above	Below
5	+	+	+	+
2	-	-	-	-
2	-	+	-	-
1	+	+	-	-
1	+	-	+	-
1	-	+	+	-
1	-	+	+	+
1	-	+	-	+
0	Any other combination			

upper limit of the luminance scale. Hence the grouped thresholds represent off scale thresholds).

The thresholds at 30° excentricity in the nasal field showed that six out of the fourteen patients had reduced thresholds either above or below the horizontal meridian or both. However, there was no indication of a step formation as the greatest discrepancy between the two readings was 0.3 log units. The losses at these points represented general reductions in sensitivity. Furthermore, it appeared that reductions did not occur in the nasal field without corresponding abnormalities adjacent to the optic disc. All six individuals with reduced thresholds had either photopic, or scotopic, or both types of abnormal loss at the other test points. However, there were instances of the converse (i.e. losses adjacent to the optic disc without losses in the nasal field). This supports the idea that nasal losses are secondary to the temporal ones.

A summary of the pattern of photopic and scotopic thresholds is given in Table XXVI. Plus signs indicate thresholds within normal limits and minus signs indicate thresholds outwith normal limits. The pattern of plus and minus signs within any row indicates the combination of normal and abnormal responses for any individual under the four test conditions. Different rows indicate the combinations present in the group. Consequently/

Consequently there are five individuals with plus signs in each column, indicating that there are five individuals with normal threshold values at all points tested. In the next row two individuals are shown to have abnormal thresholds at all points tested. Because of the small numbers involved, the percentages are unreliable as indices of the likelihood of a given pattern of thresholds in a group of potential glaucoma patients. However, the importance of the patterns (and only one instance in any row is sufficient for this) is in showing that several combinations of losses are possible. Thus there is an instance of a purely photopic loss (row 4) and of a purely scotopic loss (row 7), together with mixed photopic and scotopic losses. Whether or not it is only the scotopic losses which are important in the diagnosis of early glaucoma remains an open question.

A comparison of the photopic and scotopic sensitivities at the same retinal point did not indicate any tendency for normals or abnormals to be associated with either luminance level (Chi Square Test). An equally important aspect of the classification was to place those individuals with normal thresholds in the normal category. An inspection of Fig. 116 shows that the method of limits and the forced choice procedure produce considerable fluctuation of threshold values within the limits of normality indicated by the dotted lines./

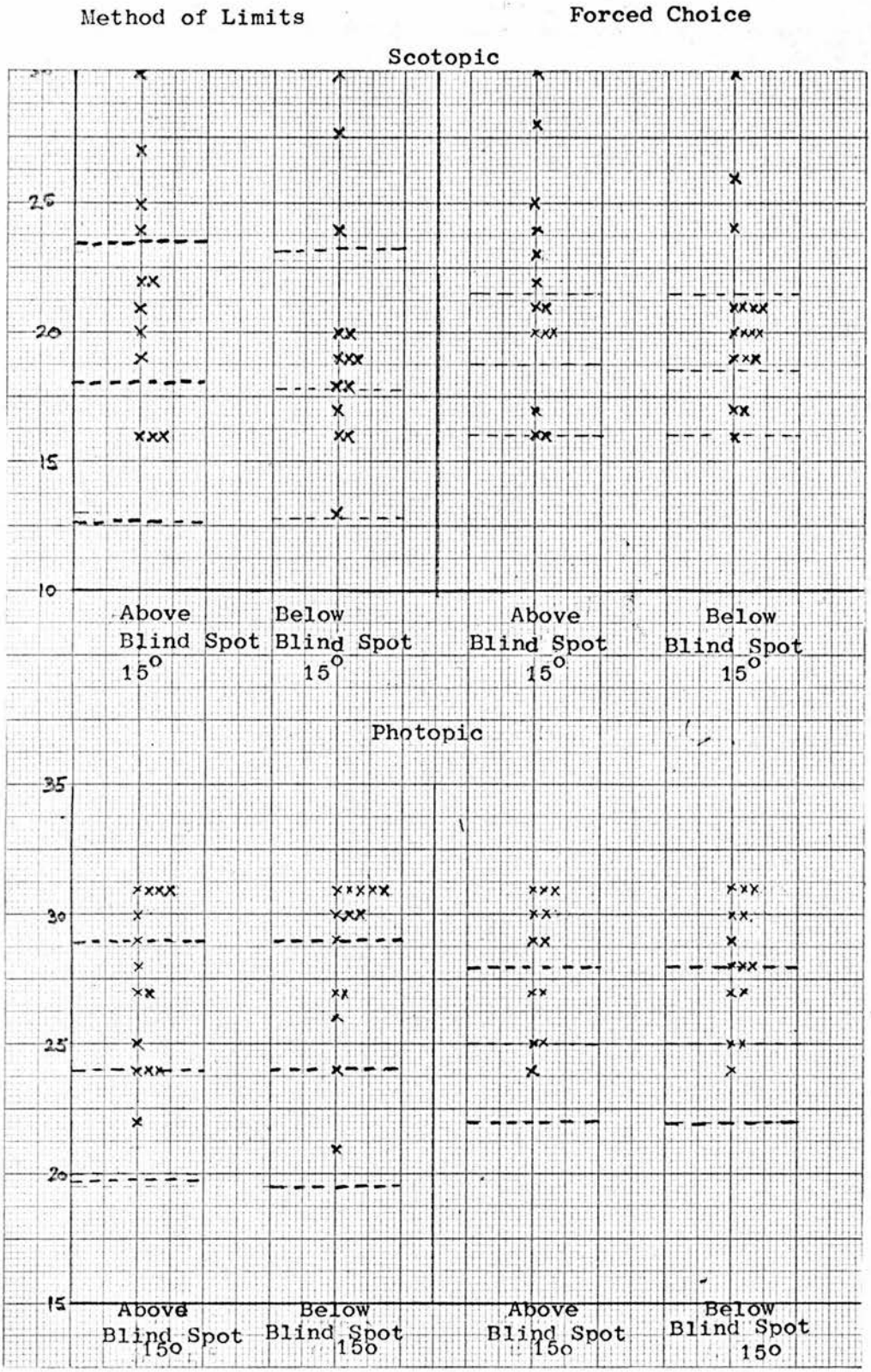
lines. Spearman rank correlations obtained between the two methods were not significant on those individuals with thresholds within the normal range. Thus the apparent significant correlation between the two methods for the total group (see page 337) is brought about by the extended range of thresholds when abnormal values are included. Similarly, correlations between photopic and scotopic forced choice thresholds in the normal category and at the same retinal point, showed no significant association. It appears, therefore, that within the normal range, the two measures are in fact independent.

These results indicate that the normal perimetric method agrees closely in categorising individuals as normal or abnormal, with the refined forced choice method assumed to give the true threshold. This agreement is good in a clinical situation. However, if the agreement is assessed on those individuals falling within the normal range, there is no significant correlation between the two methods.

To summarise: in a group of potential glaucoma patients with good Snellen acuity and full Bjerrum fields, the scotopic thresholds indicate abnormal results in 57% of the patients, and the photopic results indicate abnormal results in 57% of cases. In addition, there is no evidence for a particular pattern of either scotopic or photopic losses. Several patterns are/

Figure 117

Thresholds by the method of limits and method of forced choice under Scotopic and Photopic Conditions



are possible. Which pattern is particularly associated with subsequent glaucoma cannot as yet be identified.

4. Subgroup 2

This group consisted of those patients who had a diagnosed chronic simple glaucoma in one eye but whose other eye showed no abnormalities on ophthalmoscopy, tension, Bjerrum fields or Snellen acuity. For a description of the method, see page 331.

(i) Results

The group consisted of 14 patients with a mean age of 63 years and a mean tension value of 17.8 mm. The individual threshold values under scotopic and photopic conditions are shown in Fig. 117 . The means and standard deviation of the group and of the normals are also shown in the figure.

(ii) Discussion

The difference in methods of determining the threshold again made a marked difference in this subgroup regarding the classification of individuals. Under scotopic conditions four individuals were judged to be abnormal by the method of limits, and six by the forced choice method. Below the blind spot there were three abnormal threshold values by both methods. Once again the distribution of threshold values within the normal limits was markedly affected by changing the method in which thresholds were determined. Of the four individuals initially found to be beyond normal/

normal limits, all four were subsequently found to have abnormal thresholds. The forced choice method had the effect of adding a further two to this list. These two were in fact borderline cases when the normal range was extended. The difference between the two methods appeared to lie in the increased detection of abnormals by the forced choice method. The method of limits seldom classified thresholds as false positive, i.e. as abnormal when in fact they were normal. Whether or not the increased detection warrants the additional time necessary for the forced choice methodology is a practical problem to be decided by the needs of the clinician.

In this subgroup, all individuals who had abnormal thresholds below the blind spot were included in the abnormal group above the blind spot. Thus of six abnormal thresholds under scotopic conditions, three were abnormal both above and below the blind spot, and three were abnormal above, but had normal thresholds below the blind spot.

The photopic thresholds are plotted in Fig. 117. Over all there was a greater proportion of abnormal thresholds under photopic conditions than under scotopic. (As in Subgroup 1, the grouping of results is an artefact due to the upper limit of the luminance scale). Above the blind spot there were five abnormals under standard threshold measurements, and this increased to seven/

T A B L E XXVII

Pattern of Individual Thresholds
(+ normal - abnormal)

N	Scotopic		Photopic	
	Above	Below	Above	Below
6	+	+	+	+
1	-	-	-	-
2	+	+	-	-
3	-	+	-	-
1	-	-	+	+
1	-	-	-	+
0	Any other combination			

seven abnormals under the forced choice procedure. The original five were included in the seven. Below the blind spot there were eight individuals having abnormal thresholds by both methods and they were the same eight in either case. Taking the total photopic thresholds for this group, five individuals had abnormal thresholds at both retinal locations, two had abnormal thresholds below but normal thresholds above the blind spot, and one had an abnormal threshold above but a normal threshold below the blind spot.

Thresholds in the nasal field at 30° excentricity indicated that four individuals had reduced sensitivity. However, the reduction was similar above and below the horizontal meridian, and there was no indication of 'step' formation. (The greatest discrepancy between the two thresholds for any individual was only 0.2 log units). Of the four individuals with abnormal thresholds in the nasal field, all four had abnormal values adjacent to the blind spot. There was no instance in the group of abnormal thresholds existing at 30° excentricity in the nasal field, and the presence of normal thresholds at 15° excentricity in the temporal field. Again the nasal losses appeared to be secondary to the temporal ones.

The relationship between the photopic and scotopic thresholds for any individual is summarised in Table XXVII (cp. page 346 and Table XXVI). As in the previous/

previous subgroup, the importance of the Table is in showing that several combinations of normal and abnormal threshold values are possible in both scotopic and photopic vision. There does not appear to be one particular pattern of abnormality in any row which can be said to be characteristic of this population. As stated previously (page 346) it is not known which type of loss is associated with a glaucomatous condition. If it is the scotopic losses which are important in this respect, then there are in all six individuals out of the fourteen tested who appear to be at risk.

In summary, in a group of unilateral glaucoma patients the unaffected eye (as assessed by acuity, visual fields, ocular tension and ophthalmoscopic appearance), was tested. Both photopic and scotopic losses were found. Forty-three per cent of patients in the group showed scotopic losses. Fifty per cent of patients showed photopic losses and forty-three per cent of patients had normal thresholds for all four test conditions.

Finally, three individuals were tested who were relatives of glaucoma patients. None had any sign of visual abnormality. Thresholds values were all within the normal range under both scotopic and photopic conditions. However, the individual values did range over 0.5 log units, with one individual's threshold values approaching the upper limits of normality above the blind spot. Clearly no inferences can be drawn/

drawn from such a small number. However, the forced choice method does lend itself to similar types of genetic study where the accurate placing of individuals within the normal range may have important consequences.

5. Conclusions

Conclusionsfrom this study are as follows:-

The signal detection methodology is more sensitive in the detection of abnormal threshold values. In addition the variance of normal population values is considerably reduced by the forced choice method. The application of this method is desirable if precise detection rates are required. This may be necessary in normal population studies and in studies of clinical groups. However, there is a correlation between the forced choice method and the conventional perimetric method of limits when abnormal values are included in the sample. This occurs because both methods correlate with the common factor of deterioration. When abnormal values are excluded, the threshold values within the normal range are uncorrelated. As the detection rate produced by the forced choice method may be considered to be the 'true threshold', the normal method is not adequate for studies in which the thresholds values within the normal range are required. This may include genetic studies where minor variations in thresholds become important.

The study provided information on the psychometric/

psychometric function at 15° excentricity in the temporal field. The psychometric function under scotopic conditions covered a range of 0.6 log units, and under photopic conditions covered a range of 0.5 log units. Pupil diameter appeared to be a factor in the determination of scotopic values but was unrelated to photopic thresholds. Age correlated with threshold values under both conditions and also with the intra ocular tension. Scotopic and photopic forced choice thresholds at the same retinal point were related when abnormal thresholds were included but unrelated when thresholds within the normal range were compared.

In a study of potential glaucoma patients, and in a study of patients with chronic simple glaucoma in which the unaffected eye was tested, approximately half the patients had abnormal threshold values under either scotopic or photopic conditions or both. There was no unique pattern of losses suggested by either group. Several patterns occurred, with scotopic or photopic losses appearing in isolation or together in a mixed functional loss. It is not known which type of loss is characteristic of glaucoma, although it is generally believed that rod losses are prevalent and might represent the first signs of deteriorating function (ZUEGE and DRANCE, 1967).

The occurrence of photopic losses was in keeping with reported colour vision losses in glaucoma and in/

in ocular hypertensives, although it was not known how increment threshold measurements might be related to colour vision results in this situation. If colour vision losses are related to photopic increment threshold losses, Gruetzner's suggestion that colour vision losses are related to visual field losses was born out by the existence of correlations between photopic and scotopic thresholds (assuming that the visual field as reported by Gruetzner is a measure of rod function). However, these correlations disappeared if their calculation was based on those individuals within the normal limits. Consequently the mechanism for colour vision may be unrelated to the mechanism underlying increment thresholds. The clinical importance of photopic and scotopic increment thresholds losses, and colour vision losses, can only be assessed by a longitudinal study, which follows the progress of patients falling into either the abnormal or normal categories on each of the tests.

c.) RETINITIS PIGMENTOSA

This visual function study was carried out in the context of a detailed clinical analysis of pigmentary degeneration of the retina. Its purpose was to examine the distribution and the sequence of fundus changes within the maculararea. In this section the emphasis is on functional changes and on the relationship between/

between function and structure.

Background

The visual function losses associated with this condition are of many types. Dyschromatopsias of the yellow/blue and red/green axis have been reported, although it is the yellow/blue defect which appears to be most characteristic of the defect.

Early reports of yellow/blue defects are by BULL (1883) and KOELLNER (1906). More recent authors who have confirmed the yellow/blue dyschromatopsia are:- FRANCOIS and VERRIEST (1966); OHTA (1957); COX (1960, 1961); VERRIEST (1967); BOZZONI (1959); GRUETZNER (1962); FRANCOIS et al (1972). On the other hand a red/green dyschromatopsia has been reported in retinitis pigmentosa by RIEGER (1925); FRANCOIS and VERRIEST (1966); OHTA (1957); VERRIEST (1967); FRANCOIS et al (1972).

If both types of dyschromatopsia are present in this condition, what is the incidence of either type? In the Francois and Verriest study of 11 patients, 9 had yellow/blue dyschromatopsias, 1 had a dyschromatopsia without axis, and 1 had a deuteranomalous colour defect. However, the authors noted a wide fluctuation in the results, and the tendency for the specific type of defect to be ill-defined. In the study by COX (1960, 1961), 9 out of 16 patients had normal colour vision. All the remaining 7 had yellow/blue defects which were at the trichromatic stage in 5 patients and at the/

the dichromatic stage in 2 patients. No red/green defects were reported.

In a more comprehensive study by Verriest in 1967, 60 eyes were examined. The majority of cases showed yellow/blue defects. Only occasionally were acquired dyschromatopsias of the red/green type or the type without axis found. When red/green defects did occur, there was a tendency for the mid-matching point to be shifted towards the red. In a small group of patients with central pigmentary retinopathy, Verriest found parallel colour vision results with a majority of yellow/blue defects, and an occasional red/green defect with a shift in mid-matching point towards the red. Colour vision again appeared to be affected when visual acuity was normal.

All the above studies record a high percentage of yellow/blue defects with an occasional red/green defect present. Deterioration of colour vision which reaches total achromatopsia has been reported by several authors (NETTLESHIP, 1909; PILLAT, 1930; WAARDENBURG, 1930; GRUETZNER, 1963), but this may represent a later stage of deteriorating vision. In fact attempts to explain the type of colour defect have often focussed on the stage of deterioration in the disease. For example OHTA (1957) divided the development of the deterioration by means of colour vision tests into three stages. In the first stage the red/green equation/

equation was normal and the 100 hue scores were normal, providingthe illumination level of the test was high. The second stage consisted of a shift of mid-matching point (MMP) on the red/green equation towards the red, and by tritan type of 100 hue profile. The third stage consisted of the enlargement of the red/green matching range principally towards the green (so redresssng the former asymmetry about the MMP) and a corresponding anarchic 100 hue profile. The colour defect was said to resemble foveal tritanopia in a normal subject. Similarly VERRIEST (1964) thought that yellow/blue defects were an early sign of deteriorating vision, which could often occur when visual acuity was normal. The dichromatic stage of the yellow/blue defect could be reached when visual acuity was reduced to 0.7.

Other studies of visual function of a more general nature have revealed the following features. Firstly, reductions in the size of the visual field with associated night blindness represent one of the classical features of the disease. In perimetry TRAQUAIR (1927) and SLOAN (1942) both described the reductions in the size of the visual field to a blue object. Again ZEAVIN and WALD (1956) used blue and orange test objects to study achromatic thresholds at different locations in the visual field. The authors showed that pigmentary retinopathy selectively affected the scotopic system. At the fovea photopic thresholds could be normal even/

even when 'tubular vision' was present.

However, in addition to purely scotopic losses, there are several reports of raised foveal achromatic thresholds. For example HAIG and SALTZMAN (1955) showed that the luminance difference thresholds were more rapidly affected than the visual acuity results, and ZANEN (1959) found raised achromatic thresholds but normal photochromatic intervals. In addition, it appeared that the condition could give rise to losses of sensitivity to long wavelengths. This would account for the protanomalous shift on the red/green equation reported by OHTA (1957).

The implication that both photopic and scotopic systems are affected in retinitis pigmentosa has received confirmation from FRANCOIS et al, (1972). In a recent study of pericentral and central pigmentary retinopathy, the authors found that there were often both rod and cone dysfunctions although the rod system was most affected. Cone dysfunctions were shown by abnormal colour vision results in all cases, which followed the sequence of changes as above, from yellow/blue and red/green through to total achromatopsia. No patients showed normal E.O.G.'s or E.R.G.'s and it was concluded that E.O.G. abnormalities were early indications of deterioration. Dark adaptation data was evenly divided in the 9 cases studied between normal, slightly abnormal, and grossly abnormal. Because of the small/

small numbers involved, no intercorrelations between functional and bioelectrical anomalies were possible.

Present Study

The population consisted of patients attending the hospital with a degenerative condition of the retinitis pigmentosa type. They were subsequently referred to a retinal function unit, where extensive studies were carried out. Information was gathered from the following different sources:-

1. Clinical assessment - Case history and serological studies - A complete ocular examination including: visual acuity, visual fields, binocular indirect ophthalmoscopy, slit lamp and biomicroscopy of the retina.
2. Intravenous Fluorescein Fundus Angiography (I.V.F.) After intra-venous injection of the dye fluorescein, rapid frame fundus photography, using blue light, revealed the pattern of the retinal and choroidal circulation as the fluorescent dye passed through the ocular blood vessels.
3. Electrophysiological tests - Electro-oculography (E.O.G.): Electro-retinography (E.R.G.) A standard technique (ARDEN et al, 1962) was used for the E.O.G. measurement. The values obtained were compared with normal values recorded for persons of the same age (ADAMS, 1973). For the E.R.G. a Low Vac contact lens electrode (ECHTE and PAPST, 1962), conventional/

conventional amplification and oscilloscopic recording were employed. The stimulus was a stroboscopic flash 10 micro seconds long of varying intensity (0.03, 0.09, or 0.3 joules/flash) situated directly in front of the patient at a distance of 60 cms.

4. Psychophysical tests - Dark Adaptation (page 254); Static Perimetry (page 220); Ishihara (page 145); Farnsworth Munsell 100 hue test (page 156); Anomaloscope (page 179).

A total of 52 eyes were examined. Results are presented for:-

1. structural abnormalities
2. functional abnormalities
3. inter-relations between structure and function

1. Structure

(i) Method

The degree of abnormality of the pigment epithelium was assessed by a combination of ophthalmoscopy and fluorescein fundus angiography. It was assumed that different types of change were manifestations of a degenerating condition of the pigment epithelium (DUKE ELDER, 1968). Each area in each individual fundus was classified into one of four categories.

These were:

1. Normal
2. Slightly abnormal/

abnormal/

3. Abnormal

4. Grossly abnormal

Results are presented for A.) General Fundus Changes and B.) Specific changes within a 20° area of the fovea.

(ii) Results

A.) General Fundus Changes

Abnormalities were present in the following ways.

1. Pigmentary disturbances

a.) Distribution

(i) Regions affected were: equatorial 83% peripapillary 80%: perimacular 70%: macular 50%.

(ii) No significant differences (Chi Square Test) were found in the incidence of disturbance between the upper and lower halves of the fundus, or between areas nasal or temporal to the disc.

b.) Types

(i) Pigment Epithelium (P.E.)

a.) a whitish change was seen in 98% of eyes

b.) a reddish change was seen in 42% of eyes

c.) depigmentation was seen in 100% of eyes

(ii) Neural Retinal

a.) Fine pigmented granules (P.G.) were seen in 100% of eyes.

b.) Bone corpuscles (B.C.) were seen in/

in 83% of eyes.

c.) Large pigment clumps (L.C.) were seen in 54% of eyes.

d.) Retinal vascular sheathing by pigment was seen in 85% of eyes.

2. Retinal Changes

a.) Retinal Vascular change

Narrowing of retinal arteries was seen in 67% of eyes. It also occurred in the veins in 71% of these eyes. Retinal circulation was sluggish in 39%.

b.) Neural change

Advanced cases showed retinal thinning on stereoscopic fundal examination.

3. Choroidal Changes

a.) Vascular changes

(i) choriocapillaries were found to underlie areas of absent P.E.

(ii) Other choroidal vessels

Some intermediate sized vessels disappeared bordering areas of absent choriocapillaries.

b.) Pigmentary changes

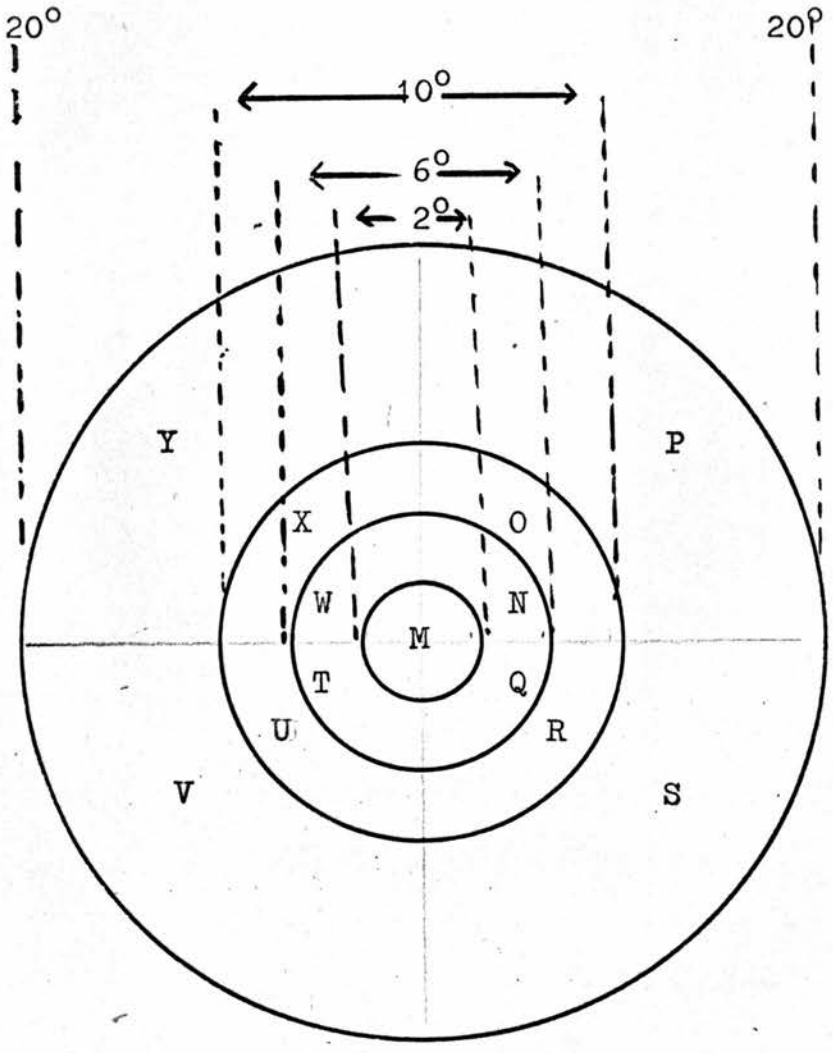
In the intermediate stages the choroidal pigment seemed to remain normal.

4. Optic Disc Changes

Pallor of the optic disc was seen in 26 eyes (50%). In only 16 of the 26 eyes was the/

Figure 118

FUNDAL AREAS SELECTED FOR STRUCTURAL ANALYSIS



Intersection of horizontal and vertical lines corresponds to fixation point.

New Variables

Parafovea	= O + R + U + X
Perifovea	= P + S + V + Y
Fovea	= N + Q + T + W + M
Foveal Surround	= N + Q + T + W
Macula	= Total 20° area

the disc of waxy appearance. Retinal arterial narrowing was seen in 22 of the 26 eyes with pale discs, and in 13 of the 26 eyes with normal discs.

B.) Central Fundus Changes

The areas of Fig.118 make up a total circular area of 20^{o} diameter about the fovea. In addition to the letters denoting specific areas, new variables have been defined by combinations of letters. The general structural classification within any area is given in Table XXVIII, which shows the number of eyes and the relative frequency of eyes in any category.

(iii) Discussion

The sequence of general pigmentary changes (see page 362) appeared to begin with a whitish or reddish appearance of the pigment epithelium associated with the release of fine pigment granules into the deep layers of the retina. Subsequently these fine granules became aggregated into large clumps, bone corpuscles, or venous sheathing. For a full discussion of fundus changes see ADAMS, ASPINALL, HAYREH (1972). The particular emphasis in this section is on the analysis of the changes in central areas (Fig. 118 Table XXVIII)

Inspection of Table XXVIII and Fig.118 shows that the degree of abnormality increases in a regular fashion with distance from the fixation point. For example in/

T A B L E XXVIII

CLASSIFICATION OF STRUCTURE

Frequency of cases in the 4 categories for each region of Fig.11

Retinal Region	Category I		II		III		IV	
	N	%	N	%	N	%	N	%
M	25	49	10	20	8	15.5	8	15.5
N	26	50	12	23	6	12	8	15.0
O	14	27	20	39	11	21	7	13
P	12	23	27	52	9	17	4	8
Q	25	48	13	25	5	10	9	17
R	15	29	19	37	11	21	7	13
S	10	19	27	52	10	19	5	10
T	24	46	12	23	6	12	10	19
U	14	27	21	40	10	19	7	13
V	10	19	28	54	10	19	4	8
W	25	48	12	23	7	13	8	15
X	15	29	20	39	9	17	8	15
Y	11	21	26	50	10	19	5	10
Parafovea	15	29	18	34	13	25	6	12
Perifovea	11	21	25	48	13	25	3	6
Fovea	24	46	13	25	5	10	10	19
Foveal Surround	25	48	13	25	6	12	8	15
Macula	17	32	19	37	10	19	6	12

Category I normal
Category II slightly abnormal
Category III abnormal
Category IV grossly abnormal

in region M, (100 - 49) or 51% of eyes have abnormalities, whereas in region perifovea, (100 - 21) or 79% of eyes have abnormalities. In the parafoveal region the percentage of abnormalities is (100 - 29) or 71%. This difference between central and more peripheral regions rests on the (correct) assumption that the classification was made on the basis of the density of abnormality, rather than on the basis of the number of abnormalities in any area. A Chi square test showed that the difference in abnormality between the central and peripheral regions was significant ($p<0.05$).

A comparison of abnormalities in the nasal (T,U,V, W, X, Y) and temporal (N, O, P, Q, R, S) areas, indicated that there was no significant difference between the two. Similarly, there was no tendency for more abnormalities to occur in the upper (N, O, P, W, X, Y), than in the lower (Q, R, S, T, U, V) field. Nor was there any tendency for a particular quadrant to have more abnormalities than any other.

It appeared therefore, that the only significant difference in structural abnormalities lay in a radial direction from the intersection of the horizontal and vertical lines shown in Fig. 118. Furthermore, the degree of difference between centre and periphery was symmetrical about the four quadrants. (Compare the triplets representing the percentage of normal fundus in the four radial directions./

directions.

N: O: P = 50: 27: 23; Q: R: S = 48: 29: 19; T: U: V = 46: 27: 19; W: X: Y = 48: 29: 21)

In all cases there was a monotonic relationship between the excentricity and the amount of abnormal structure.

This relationship is in keeping with a hypothesis of sequential change, i.e. that there is a particular sequence of structural change which begins at the periphery and gradually moves towards the foveal region. (This sequence is to be contrasted with a sequence in which the type of abnormality changes, so that the type is itself an indication of the stage of degeneration). If it is assumed that the rate of degeneration, as indicated by the type of abnormality, is similar in different retinal areas, then the hypothesis of sequential change is not supported by evidence of the frequency of occurrence of category 4 in the central and peripheral regions. If the foveal abnormality represented a later stage in the development of the disease, and the rate of degeneration was similar in different retinal areas, then one would expect to find a greater proportion of grossly abnormal structure in the perifovea than in the foveal region. This is not the case. Table XXVIII indicates that there are 15% of grossly abnormal cases in region M and 6% in region perifovea, which is in the opposite direction of the/

the expectation. Either the assumptions about the rate of change are incorrect, or the hypothesis of sequential change is incorrect.

An alternative view which might reconcile the discrepancy is that there is more than one type of retinitis pigmentosa in the sample. One type is subject to sequential change from periphery to fovea. The other type has abnormalities beginning in the foveal region. On the assumption that two distinct types do exist, three patients were removed from the sample because of an aggregation of abnormal structure in the foveal region without concomitant (peripheral) abnormalities. The percentage of cases of category 4 in the remaining patients was rechecked in the central and peripheral regions. The results were not significantly changed, and there was no indication of a greater proportion of grossly abnormal structure in the peripheral zone in the restricted sample.

(iv) Summary

It must be emphasised that the conclusions on structural changes are confined to the fundal area shown in Fig. 118. Changes outwith this area have not been considered in this analysis. It is worth recalling, therefore, that the equatorial region had the greatest percentage of abnormalities(83% of any fundus region), (see page 362).

What has been established, is that within an area/

area of 20° excentricity structural changes most frequently occur in the peripheral zones of this region. The structural changes are symmetrically distributed about the fovea, so that the only significant differences between the amount of structural change in different retinal areas are in a radial direction from the fovea. This finding is in keeping with a hypothesis of sequential change in abnormalities from periphery to fovea. However, this hypothesis can only be upheld if the rates of degeneration are different in different retinal areas. Restricting the sample on the basis of two distinct types of retinitis pigmentosa did not alter this conclusion.

2. Function

(i) Method

Visual function was assessed by electrodiagnostic and psychophysical tests (see page 360). The vision of some patients in the group had deteriorated to the extent that it was impossible to test them on some of the finer functional tests. In the following analysis these patients are recorded as having missing values on the tests in question. In this section the psychophysical data have been transformed from a continuous scale into four discreet categories. These categories are labelled normal, slightly abnormal, abnormal and grossly abnormal, as in the classification of structure. However, in this case a more definite criteria for the/

the four categories was possible. The normal limit for each test was set at the 95th percentile point in a normal population, whose mean age was 38 years. (This corresponded to the mean age of the retinitis pigmentosa group). The complete set of criteria for the four categories in each test was:-

1. Corrected distance visual acuity

Grade 1	(6/5 - 6/6)
Grade 2	(6/7.5 - 6/12)
Grade 3	(6/18 - 6/24)
Grade 4	(6/36 and less)

2. Ishihara

Grade 1	4 mistakes
Grade 2	(5 - 12) mistakes
Grade 3	(12 - 19) mistakes
Grade 4	20 mistakes

3. Farnsworth Munsell 100 hue test

Grade 1	within the 95th percentile i.e. 150 error score
Grade 2	(150 - 300)
Grade 3	(300 - 450)
Grade 4	450 +

4. Differential Foveal Threshold

Grade 1	within the 95th percentile
Grade 2	up to 0.5 log units below this
Grade 3	between 0.5 and 1.0 log unit below
Grade 4	over 1 log unit below

5. Dark Adaptation/

5. Dark Adaptation

	After 4 mins. in dark		After 20 mins. in dark	
	Blue Thresholds DAB4	Yellow Thresholds DAY4	Blue Thresholds DAB20	Yellow Thresholds DAY20
Grade 1	within 95th percentile		within 95th percentile	
Grade 2	up to 0.5 log units below this		up to 0.5 log units below this	
Grade 3	between 0.5 and 1.0 log units below		between 0.5 and 1.0 log units below	
Grade 4	over 1 log unit below		over 1 log unit below	

6. Anomaloscope

RGMR - red/green matching range

RGMP - red/green mid-matching point

YBMR - yellow/blue matching range

YBMP - yellow/blue mid-matching point

BGMR - blue/green matching range

BGMP - blue/green mid-matching point

For all equations:-

Grade 1 within 95th percentile

Grade 2 30 j.n.d.'s below this

Grade 3 between 30 - 60 j.n.d.'s below

Grade 4 $>$ 60 j.n.d.'s below

Although this method of grading results represents a loss of information, it was thought necessary to simplify the data because such a wide range of visual function existed in this population. Furthermore it/

TABLE XXIX

CLASSIFICATION OF FUNCTION

Frequency of cases in five categories for each visual function te

Visual Function	Category I		II		III		IV		V	
Test	N	%	N	%	N	%	N	%	N	%
EOG	6	12	4	8	10	19	25	48	7	13
ERG	7	13	7	13	10	19	23	44	5	10
Visual Acuity	13	25	14	27	12	23	12	23	1	2
100 Hue A	15	28	12	23	3	6	4	8	18	34
" B	21	41	5	10	4	8	4	8	18	34
" C	7	13	9	17	7	13	11	21	18	34
" D	14	27	8	15	4	8	8	15	18	34
" Total	12	23	10	19	4	8	8	15	18	34
Increment Threshold	5	10	7	13	16	30	8	15	16	30
DAB4	8	15	7	13	5	10	12	23	20	38
DAY4	8	15	7	13	5	10	12	23	20	38
DAB20	7	13	1	2	3	5	23	44	18	34
DAY20	7	13	5	10	3	5	19	36	18	34
RGMR	6	12	9	17	5	10	7	13	25	48
RGMP	8	15	8	15	4	8	7	13	25	48
YBMR	3	5	6	12	4	8	14	27	25	48
YBMP	3	5	3	5	7	13	14	27	25	48
BGMR	3	5	3	5	4	8	17	34	25	48
BGMP	4	8	3	5	3	5	17	34	25	48
Ishihara	13	25	4	8	6	12	14	27	15	28
Delay time	8	15	10	19	5	10	9	17	20	38
Cross over time	5	10	3	5	5	10	21	40	18	35

Category 1 Normal
Category 2 slightly abnormal
Category 3 abnormal
Category 4 grossly abnormal
Category 5 missing values

DAB4 Dark Adaptation (Blue threshold at 4 minutes)
DAY4 " " (Yellow " " 4 ")
DAB20 " " (Blue " " 20 ")
DAY20 " " (Yellow " " 20 ")

it enabled the functional and structural data to be placed on a comparable basis.

There is an additional category (category 5) included in the Table of results which corresponds to the missing values on any test. Category 5 is more than simply an indication of the number of individuals who were not tested. In all but one case (a genuine missing value), the patients in this category were unable to carry out the test because of poor vision. It is reasonable therefore, to consider the percentage of missing values as part of the total abnormal category.

(ii) Results

An analysis of the total results showing the number and relative frequency of eyes in each category for each test, is given in Table XXIX. Additional results for individual patients are shown in Figs. 119 to 125 indicating some of the different types of functional abnormalities existing in this population. Associations between the tests were calculated by contingency coefficients. These are given in Table XXX.

(iii) Discussion

General results are discussed first followed by a selection of representative individual cases.

Inspection of TableXXIX shows that on the electro-diagnostic tests 12% and 13% of patients were considered to have a record within normal limits, while on Snellen visual acuity 25% of patients could read 6/6 or better./

T A B L E XXX

Correlations between Tests of Visual Function

Visual acuity was significantly related to the 100 hue test		(p <.01)
" " " " " "	foveal threshold	(p <.01)
" " " " " "	RGMP	(p <.01)
BGMR " " " " "	DAB20	(p <.01)
" " " " " "	DAY20	(p <.01)
Visual acuity was not " " " "	BGMR	
" " " " " " "	DAB20	
" " " " " " "	DAY20	
The EOG was significantly related to	DAB4	(p <.01)
" " " " " "	DAY4	(p <.05)
" " " " "	DAB20	(p <.01)
" " " " "	DAY20	(p <.01)
" " " " "	the cross over	(p <.01)
The EOG was not related to any other psychophysical measure		
" " " " " "	the E.R.G.	
The ERG was significantly related to visual acuity.		(p <.05)
" " " " "	RGMP	(p <.05)
" " " " "	DAB20	(p <.01)
" " " " "	DAY20	(p <.01)
The ERG was not related to any other psychophysical measures.		

better. Colour vision results were obtained on the 100 hue test and Pickford anomaloscope. Twenty three per cent of patients produced a 100 hue error score that was within the normal limits. However, of these 23% with "normal vision", 4% had clearly distinct tritanopic profiles of a typical bipolar form (see Fig. 121). The four areas of the test centred on cap Numbers 1, 23, 45, 66 were denoted as variables A, B, C, D respectively. Note that the smallest percentage of normal scores fell in region C, which correspond to one area of tritanopic confusion (see Fig. 50). This is in keeping with the reported predominance of yellow/ blue defects in retinitis pigmentosa.

This finding was even more apparent in the anomaloscope matching ranges. Table XXIX shows that both the yellow/blue and green/blue equations have the least number of patients with thresholds within the normal category (5%), and consequently the greatest total number of abnormal results of any test. Eighty per cent of the patients have a colour vision loss which has reached the dichromatic stage on the blue/green equation. However, it would be misleading to specifically associate yellow/blue defects with this condition. For instance only 12% of patients had red/green matching ranges within the normal limits. Similarly, the Ishihara test, although less sensitive, recorded only 25% of patients who made less than four/

four errors. In summary, the yellow/blue and green/blue colour discrimination was most affected in retinitis pigmentosa but there were in addition considerable losses in red/green discrimination.

The predominance of yellow/blue and green/blue losses is in keeping with a hypothesis of changing function in retinitis pigmentosa, which begins with blue/green losses and progresses to red/green losses at a later stage in the disease. Furthermore this hypothesis of sequential change in function may be investigated here, as in the section on structure, by considering the percentages in the grossly abnormal category. The hypothesis is supported if there are a greater percentage of category 4 cases in blue/green and yellow/blue than in red/green discrimination. This in fact was the case, with 13% of category 4 in the red/green matching range, 27% in the yellow/blue equation, and 34% in the green/blue equation. The difference between the red/green and blue/green percentages was significant. ($p < .05$) (The comparison across equations is legitimate because of the transformation to a uniform chromaticity scale, in which 30 j.n.d.'s represents an equivalent range of an abnormal category on any of the three equations). It appears, therefore, that with regards to function, the hypothesis of sequential change is supported by evidence from the normal and from the grossly abnormal categories./

categories.

The dark adaptation results showed that only 13% of patients had scotopic thresholds in the normal range, while 15% had normal photopic thresholds. This difference was not significant. Again the association of particularly scotopic losses with retinitis pigmentosa can be misleading. However, the predominance of gross scotopic losses can be seen from the relative percentages in category 4. Although 23% of patients had cone thresholds in this grossly abnormal category, 44% of the patients had rod thresholds in this category. Once again this is in keeping with the hypothesis that the rods are affected at an early stage in this disease.

The dark adaptation cross-over time also appeared to be a sensitive index of deteriorating vision, with only 10% of patients in the normal range and 40% in the grossly abnormal category. Similarly the increment threshold results were mostly abnormal, although in this case the percentage of cases having reached an advanced stage of deterioration was relatively small and comparable to the percentage in the 100 hue test.

The next question arising from Table XXIX is whether it is the same individuals who are classed as either normal or abnormal across different tests. Unfortunately in the present context intercorrelations between the psychophysical tests are limited in their usefulness, because the range of vision in this population is so/

so great. When this occurs the test results intercorrelate at a significant level because each test is correlated with a third dommon factor i.e. deterioration. Consequently, the tests agree in their classification of some individuals as normal and of others as abnormal. (In the section on Diabetes where the range of visual performance was smaller, a factor analysis clearly showed that different tests measured different aspects of visual function. A similar finding occurred in the section on Glaucoma). In such situations it is often the tests which do not correlate significantly with each other which are of greatest interest. However, some of the more notable comparisons are listed below.

Contingency coefficients between visual acuity and the 100 hue test, and visual acuity and the foveal differential threshold, were both significant ($p < .01$). However, the correlation between visual acuity and scotopic thresholds was not significant. The correlation between visual acuity and the red/green anomaloscope equation ($p < .01$) was significant, but that between visual acuity and the blue/green discrimination was not significant. It is clear from the lack of correlation between blue/green discrimination and visual acuity that if a deterioration in blue/green discrimination represents an early stage of degeneration, then this will only be detected by a blue/green test or tests which correlate with it. Further discussion on this is given below./

below. It is interesting that two of the tests which did not correlate with visual acuity (namely scotopic thresholds and blue/green discrimination) correlated highly with each other ($p < .01$). This suggests once again the close link between blue/green discrimination and rod activity, and is supported by the fact that no correlation existed between red/green discrimination and scotopic thresholds. Finally, the classification of the cross-over point coincided almost exactly with the classification of scotopic thresholds, so that correlations which are true for the scotopic thresholds will hold for the cross-over time.

The relationship between the electro-diagnostic tests and the psychophysical tests was as follows.

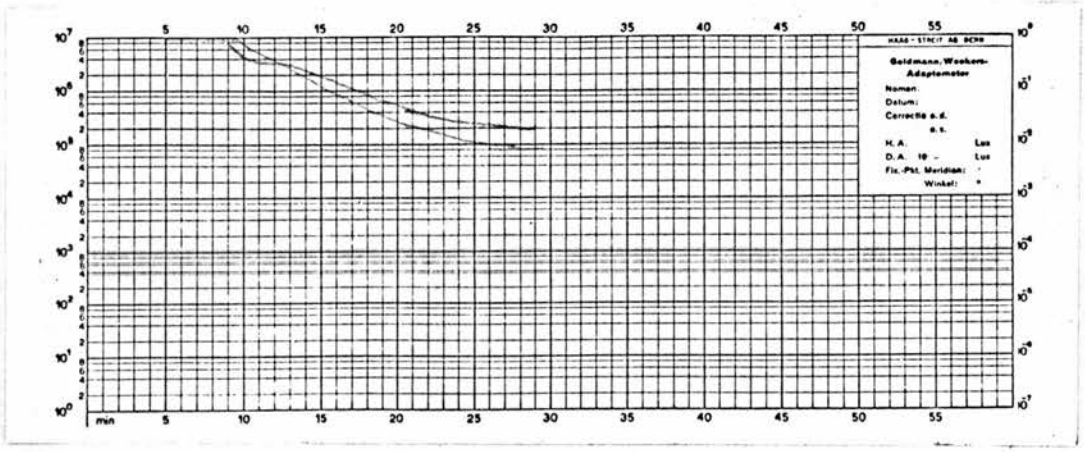
The E.O.G. only correlated significantly with some of the variables occurring in the dark adaptation experiment. These were firstly, the cone thresholds following light adaptation, secondly the final scotopic thresholds, and thirdly the cross-over time from cone to rod function. No significant relationships between either visual acuity or colour vision scores and the E.O.G. were obtained. The E.O.G. was not significantly correlated with the E.R.G.

The relationship between the E.R.G. and psychophysical tests was less clearly defined. For instance, the E.R.G. was significantly associated with visual acuity ($p < .05$) and with the mid-matching point on the red/green/

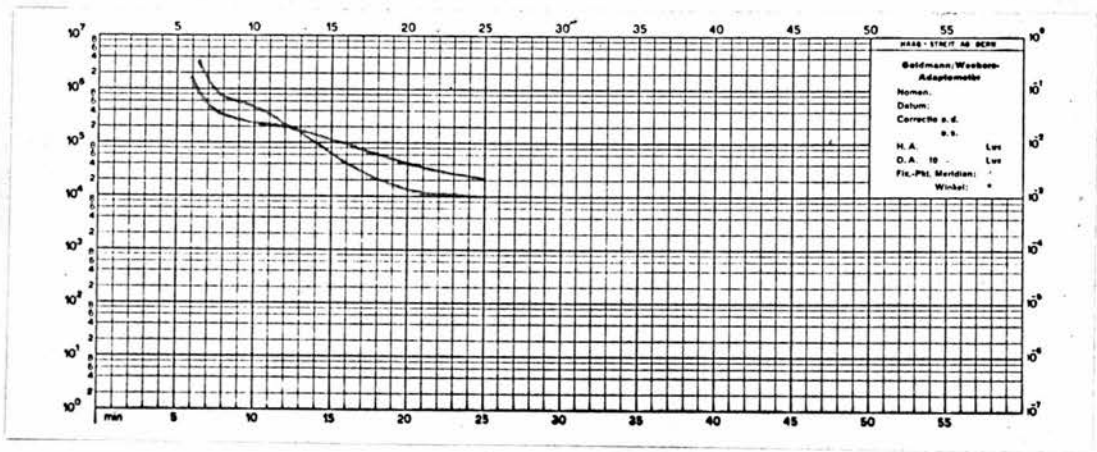
green equation ($p < .05$). It was not significantly associated with other colour vision measures. In addition the E.R.G. correlated with some of the dark adaptation variables, i.e. with the cross-over point and with the absolute level of scotopic thresholds. (It must be recalled that the E.O.G. and E.R.G. represent gross activity from the whole retinal area, whereas the largest retinal area stimulated in a psychophysical test is the 10^{o} test patch in dark adaptation).

The significant relationship between the red/green anomaloscope equation and the E.R.G., and the lack of any relationship between the blue/green equation and the E.R.G., may suggest that the E.R.G. becomes abnormal when the red/green equation is affected. This corresponds to the second stage of degeneration according to OHTA (1957). The evidence from Table XXIX supports this proposal, as there are a greater proportion of 'normals' on the E.R.G. and red/green equation than on the blue/green equation. (Unfortunately evidence from category 4 cannot be used in this instance because psychophysical abnormalities and E.R.G. abnormalities were classified in terms of different units).

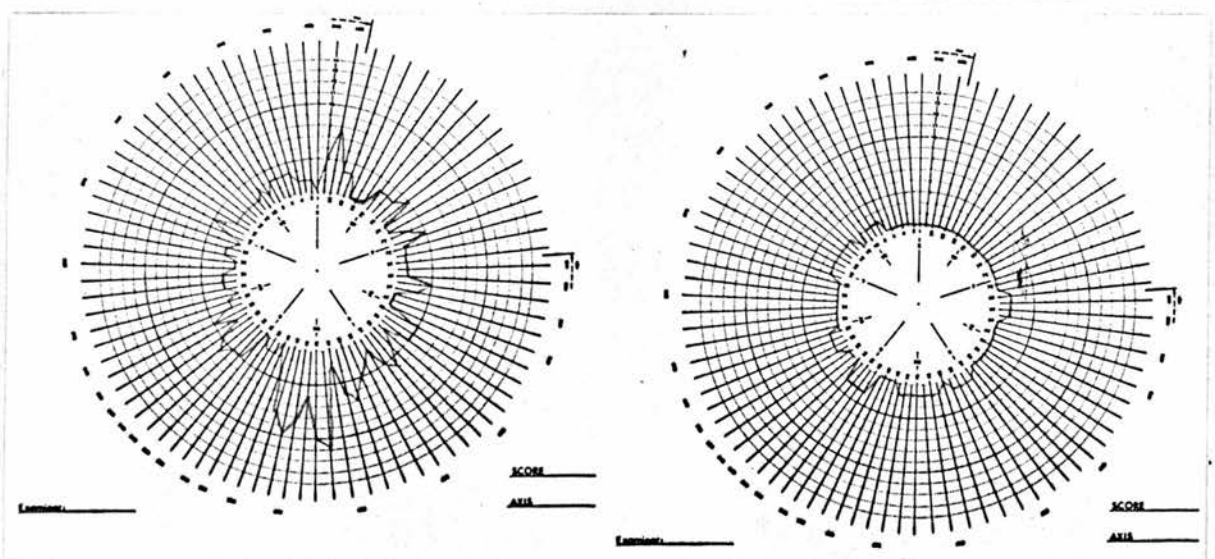
In addition to the results of the general analysis there are several interesting individual cases which require attention. The dark adaptation curves vary in several distinct ways./



Left eye



Right eye



P/N Anomaloscope

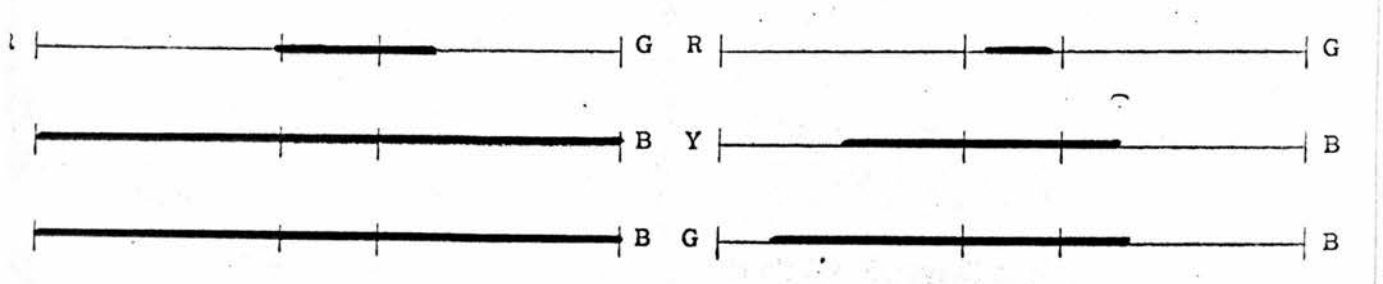
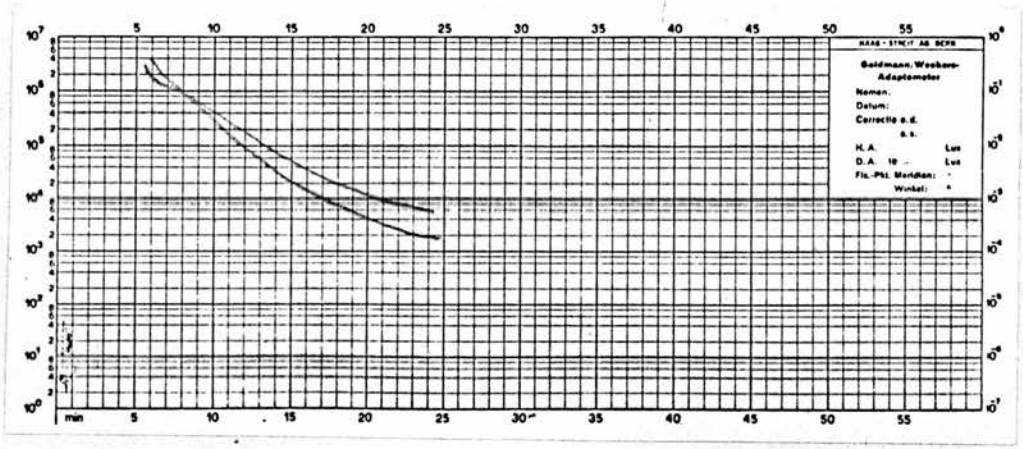


Figure 119 Retinitis Pigmentosa



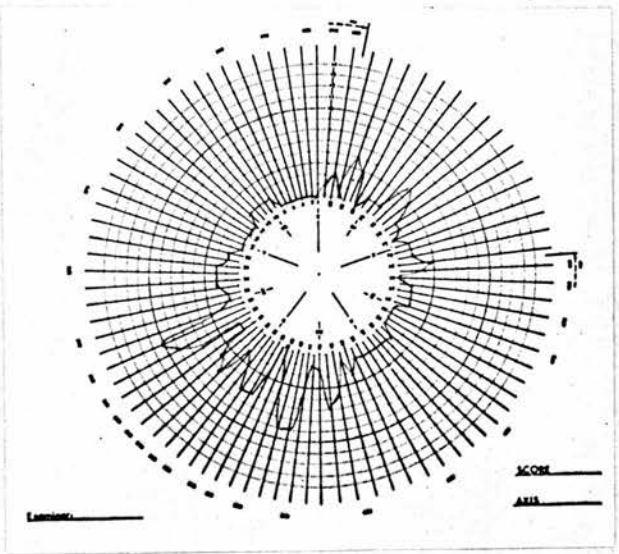
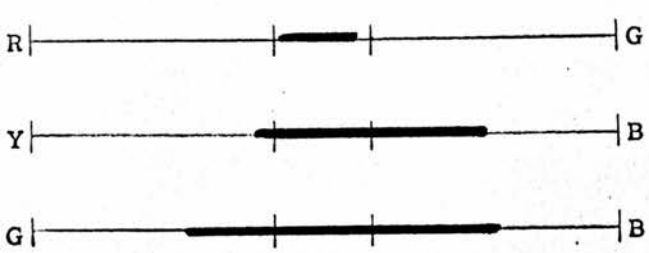


Figure 120

Retinitis Pigmentosa

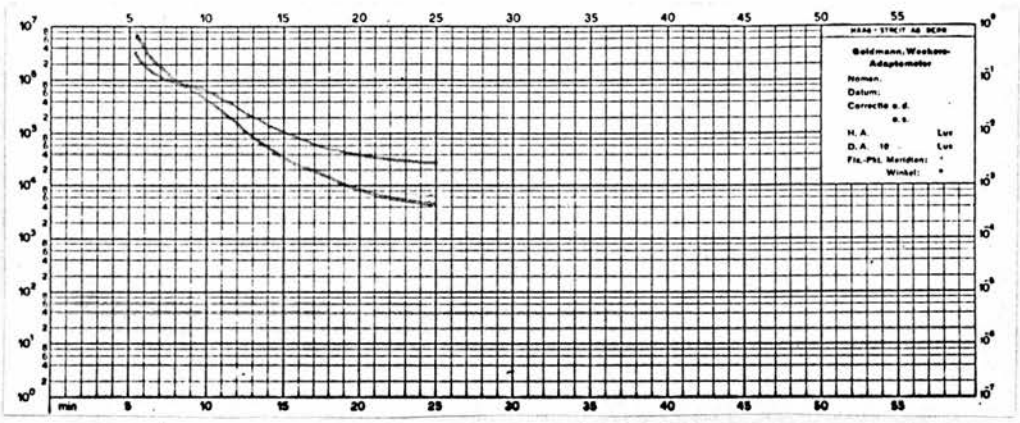
P/N Anomaloscope

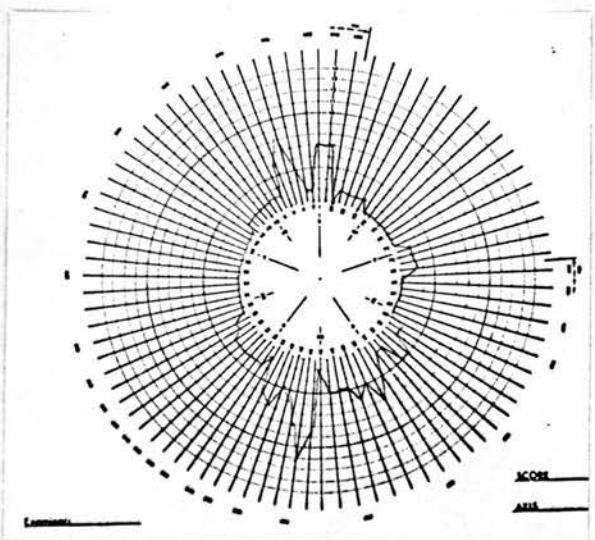


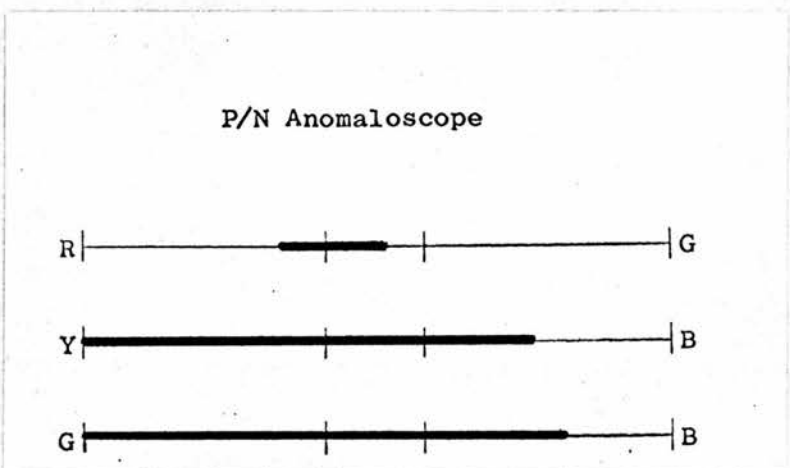
ways.

An instance of a normal cross-over time is shown in Fig. 119. However, the left eye showed generalised losses to both photopic and scotopic systems, and the scotopic thresholds were raised over one log unit above the normal limits. The right eye data on the same patient showed a normal cross-over time and normal cone function, although evidence of scotopic losses was already apparent (0.5 log units). A comparison of the colour vision data in the same patient showed that the right eye had a normal 100 hue score, and the left eye an abnormal score with a suggestion of a tritan axis. (The Ishihara score was normal in both eyes). On the anomaloscope, the right eye was within normal limits on the red/green equation but had losses on both the yellow/blue and the blue/green equations. The left eye had reached the dichromatic stage on the yellow/blue and blue/green and had an extended matching range on red/green. These results confirm rod and blue/green losses as early symptoms of deterioration before subsequent damage occurs to other visual functions.

A case in which there is a suggestion of an early cross-over time is shown in Fig. 120. Note that in this figure the rod function is still within the normal range. Of the colour vision results, the 100 hue score is within normal limits and the red/green equation is within normal limits. However the yellow/blue equation/







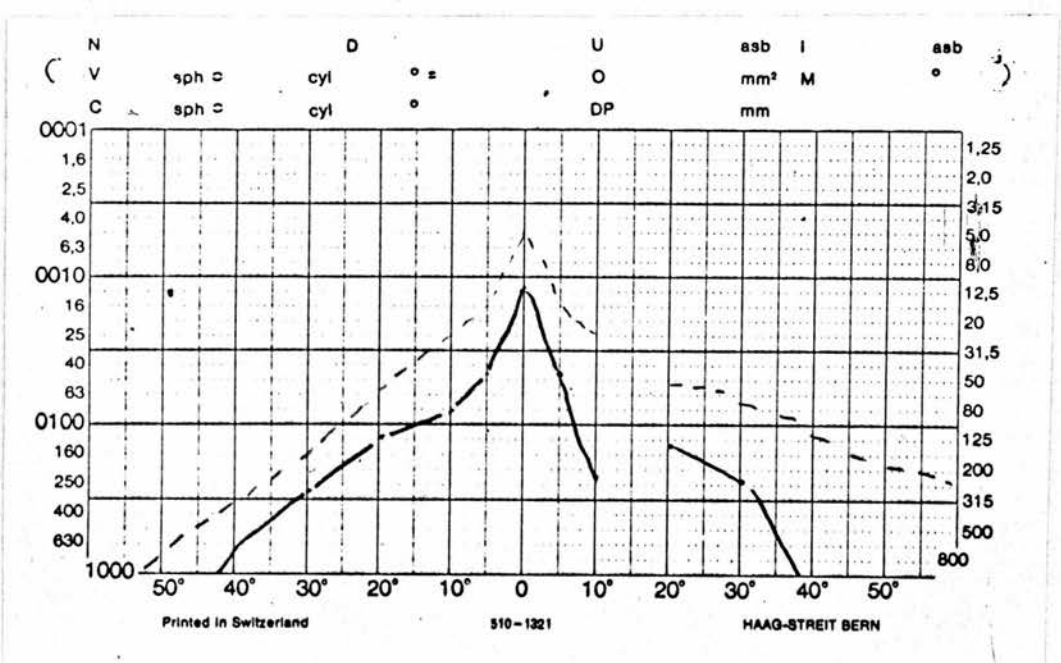
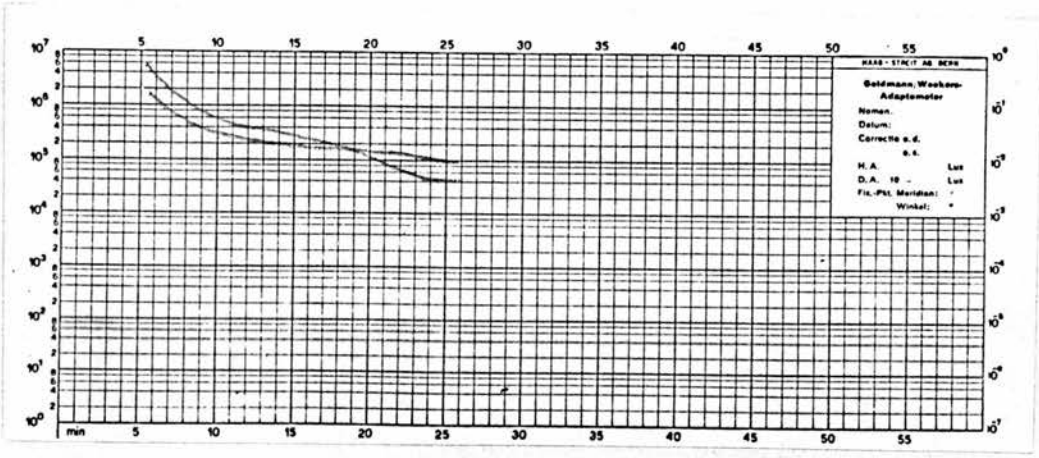
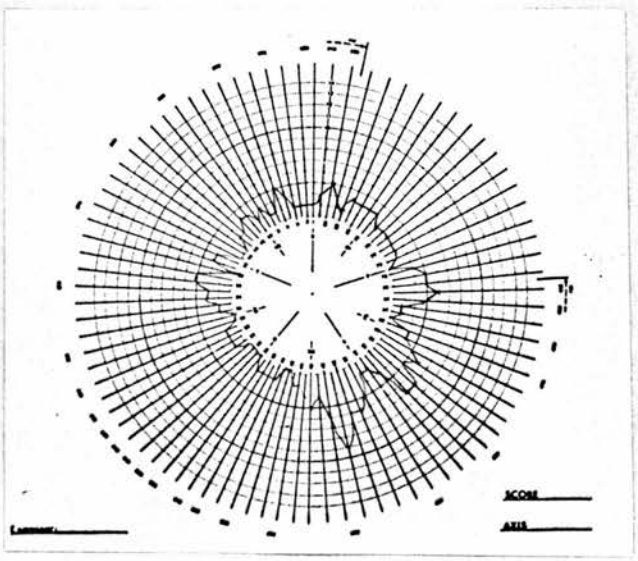
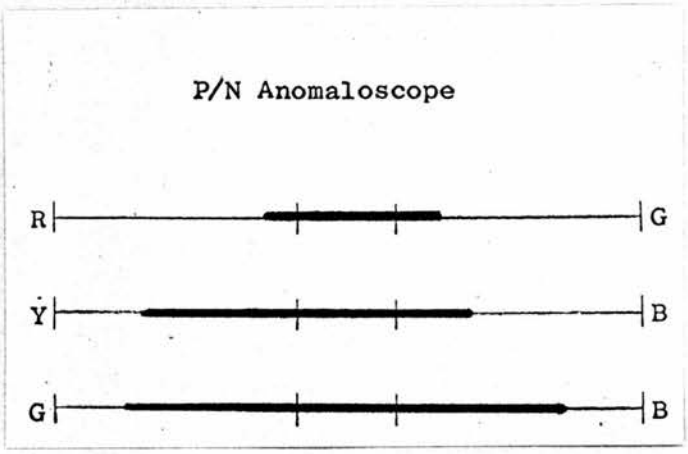


Figure 121 Retinitis Pigmentosa







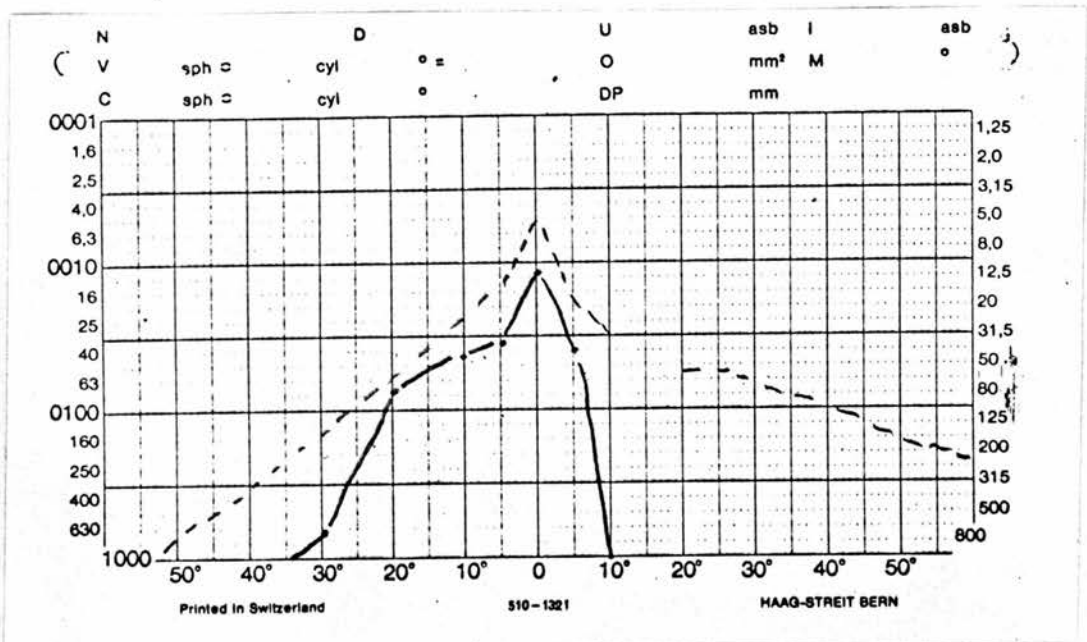
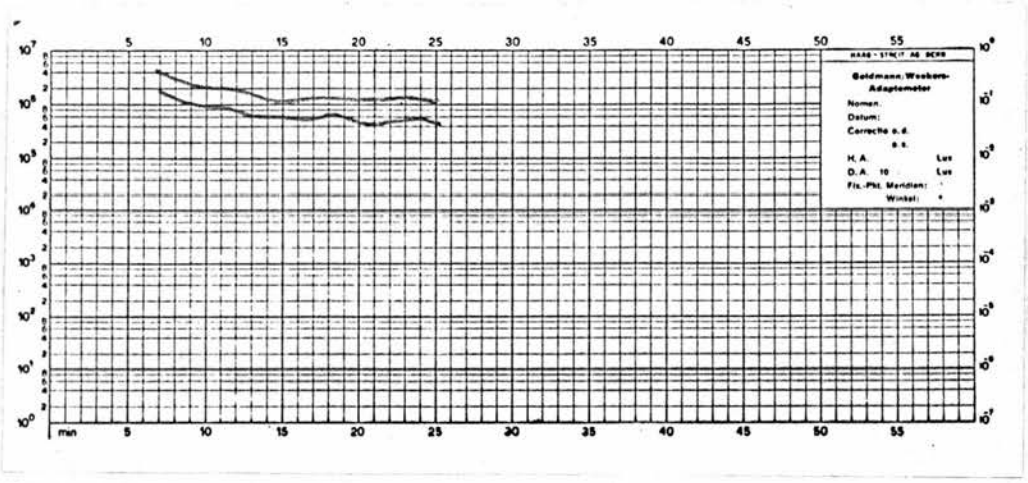


Figure 122 Retinitis Pigmentosa

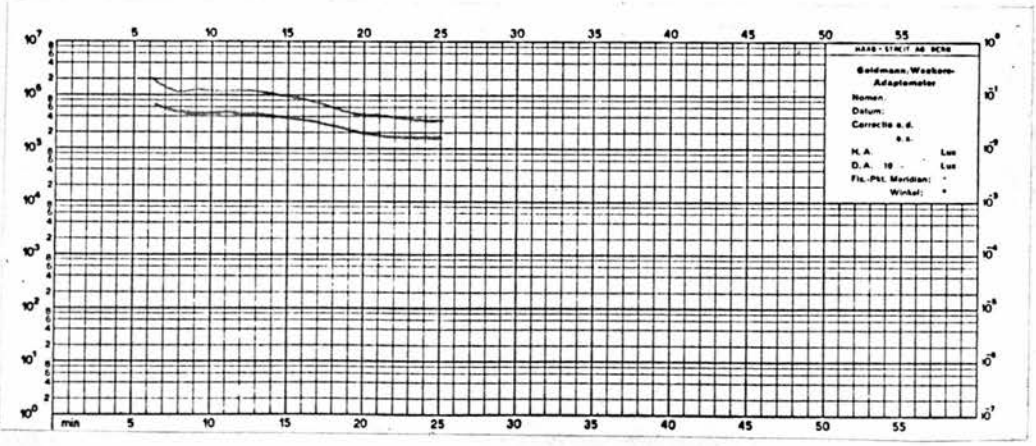
equation is already shifted towards the blue, and the blue/green equation shows generalised losses. A comparison of this Fig. with the previous one, shows that blue/green losses are common to both cases. However, in the former case the earliest sign of change from normality in dark adaptation is in the rod function while in the latter case it is the shift in cross-over to earlier times. Again Fig. 121 shows an early cross-over time with relatively normal scotopic thresholds. Here there is a classic tritan profile on the 100 hue test, generalised losses on the yellow/blue and blue/green equations, and a shift towards the red on the red/green equation. A static perimetric profile shows that there are peripheral losses in both the nasal and the temporal fields.

On the other hand, there are instances in the group of significantly late cross-over times in dark adaptation. Fig. 122 shows one such case. Note also the raised rod threshold ($\sim$ 1.5 log units). In this patient the Ishihara and 100 hue can be considered normal. However, once again the anomaloscope records losses on the yellow/blue equation (this time towards the yellow) and extended blue/green discrimination. The red/green equation is also affected. The static perimetric profile is included, showing a collapse of the temporal field and indications of peripheral losses in the nasal field./

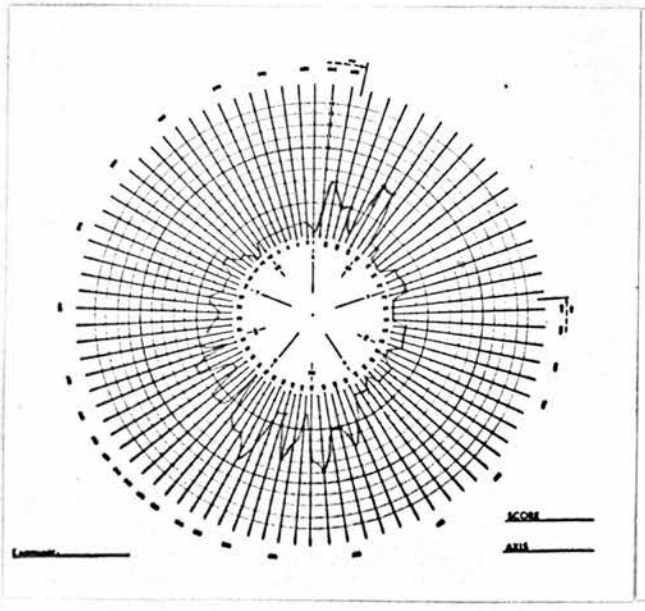
Figure 123 Retinitis Pigmentosa

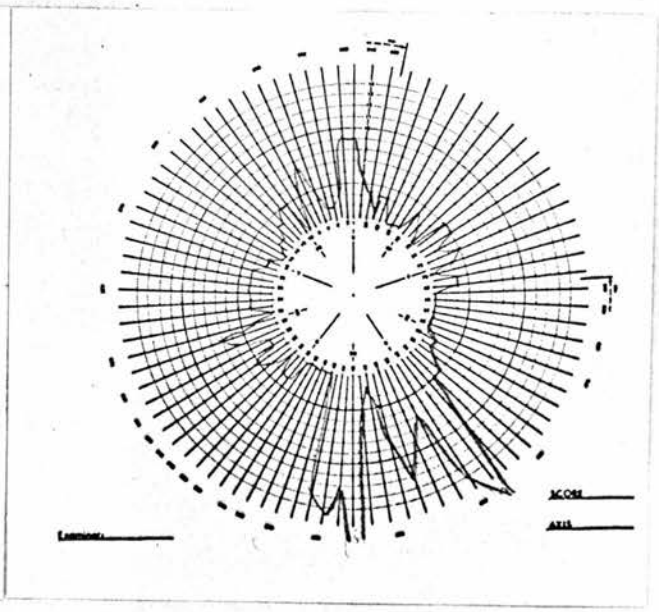


Right eye

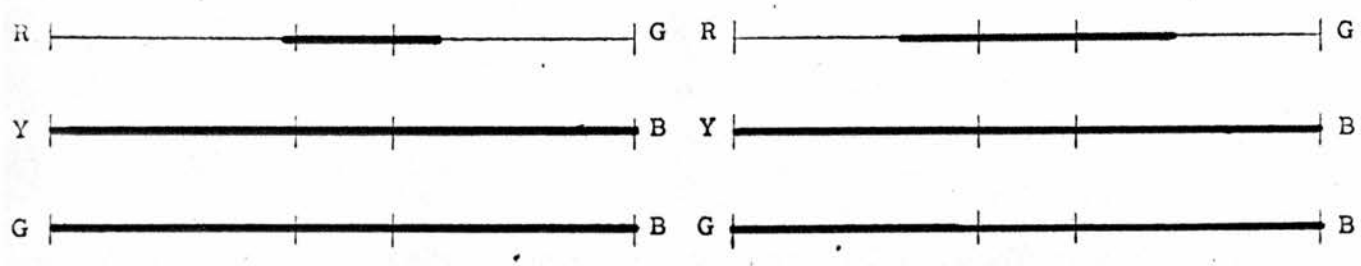


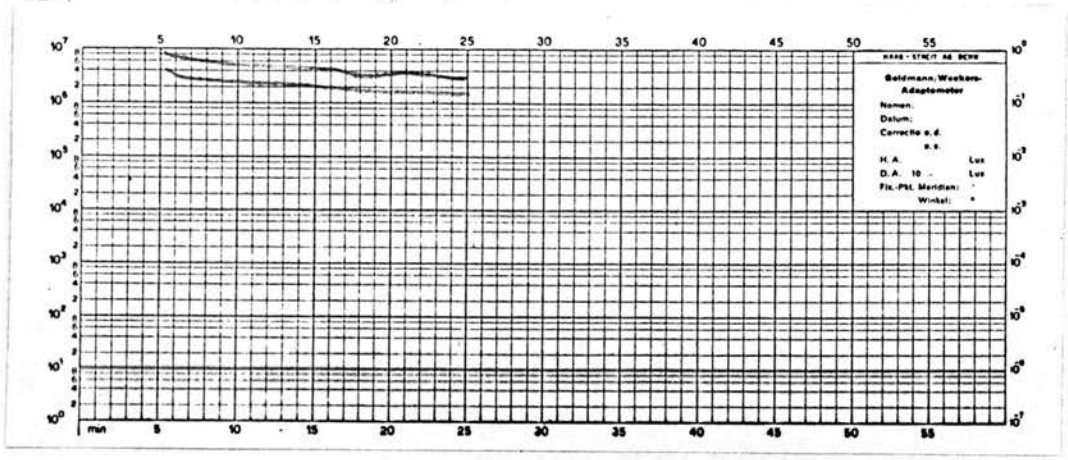
Left eye

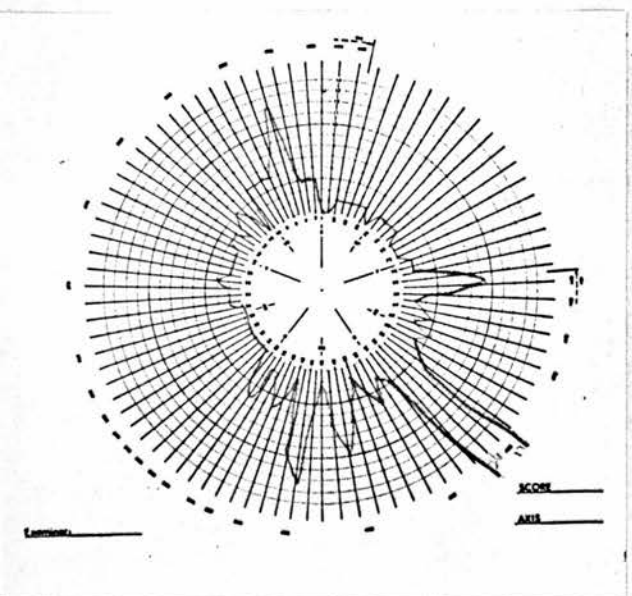


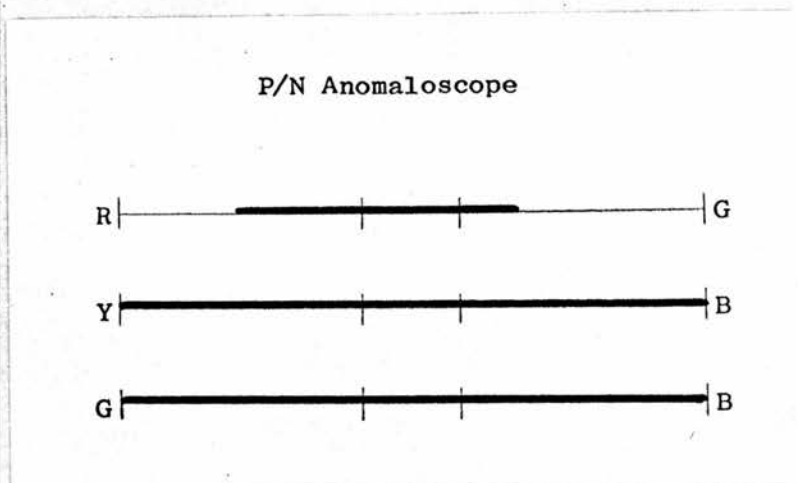


P/N Anomaloscope









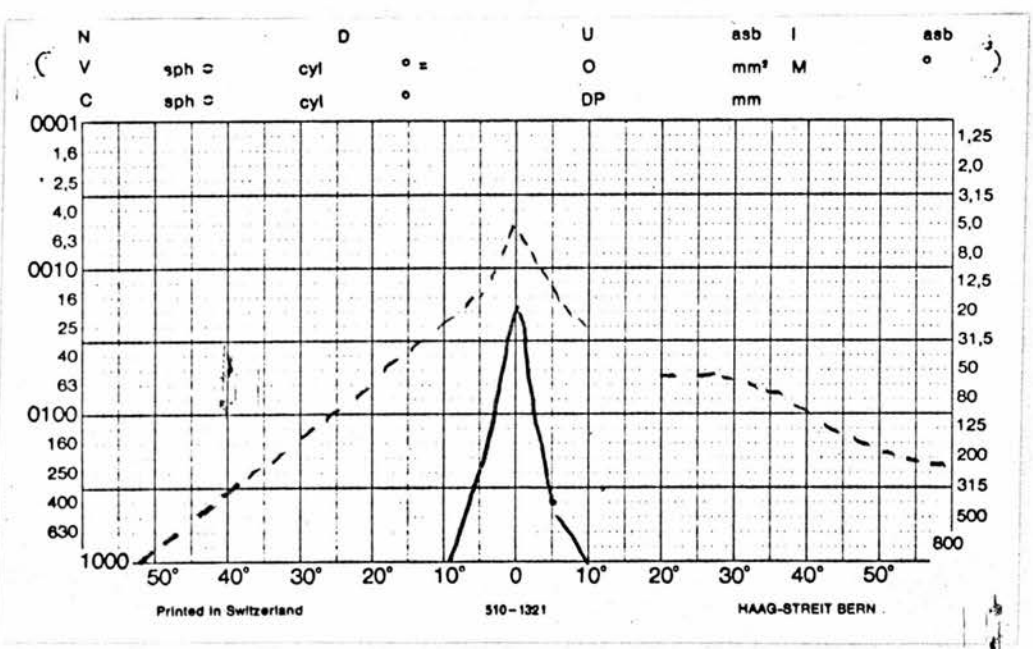
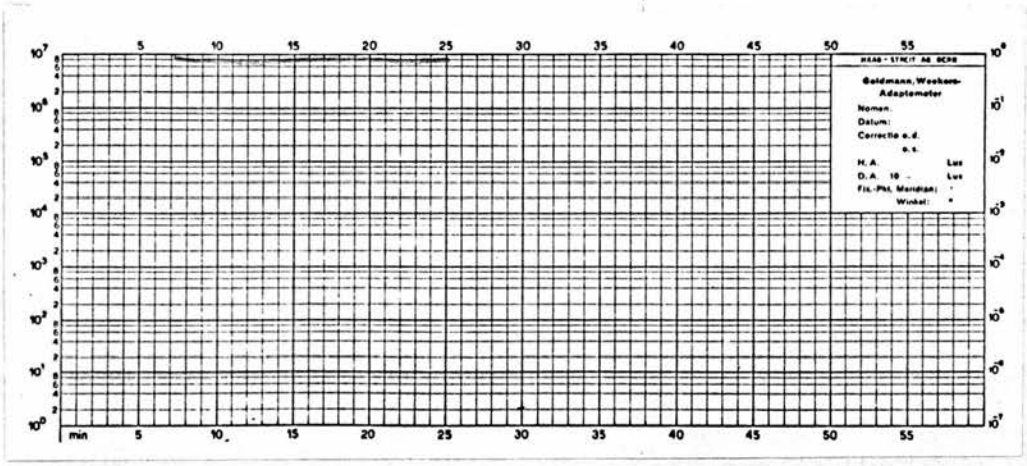


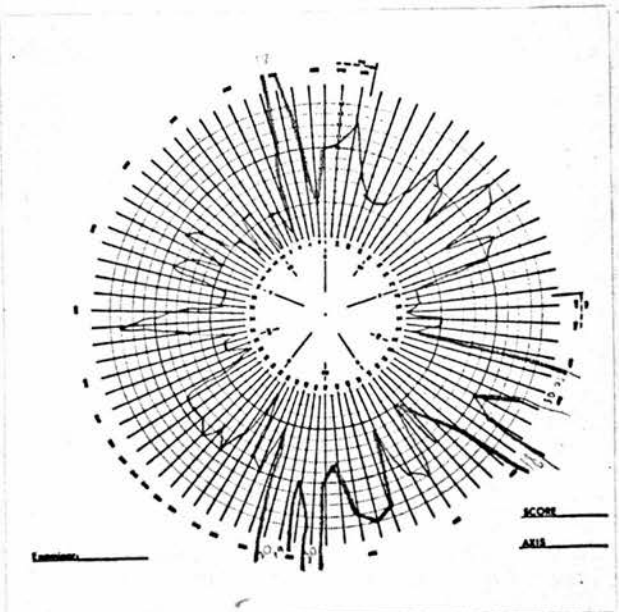
Figure 124 Retinitis Pigmentosa

field.

Finally by far the commonest type of dark adaptation curves had no cross-over, and the cones functioned throughout the adaptation period of 20 minutes. This complete loss of rod function (within the experimental limits) was associated with different colour vision results. For instance in Fig.123 both dark adaptation curves have simply cone function. The 100 hue results show that the higher error score and tritan axis is associated with a dark adaptation curve of the same form, but which has higher thresholds in the cone function ($\sim$ 0.4 log units). On the anomaloscope both eyes have reached the dichromatic stage on the blue/green equation, whereas the red/green loss in the right eye is much greater than that in the left eye. Another patient with dark adaptation thresholds at the extreme of the instrument scale is shown in Fig. 124. Here there is a suggestion of a red/green loss on the 100 hue test. This is confirmed by the anomaloscope, where although yellow/blue and blue/green equations are at the dichromatic stage, both eyes show red/green losses. The static perimetry profile shows tunnel vision in both eyes. The final stages of deterioration are shown in Fig. 125. Here dark adaptation thresholds are off scale, and both the 100 hue and the anomaloscope indicate achromatopsia.

It is not clear what significance can be attached/





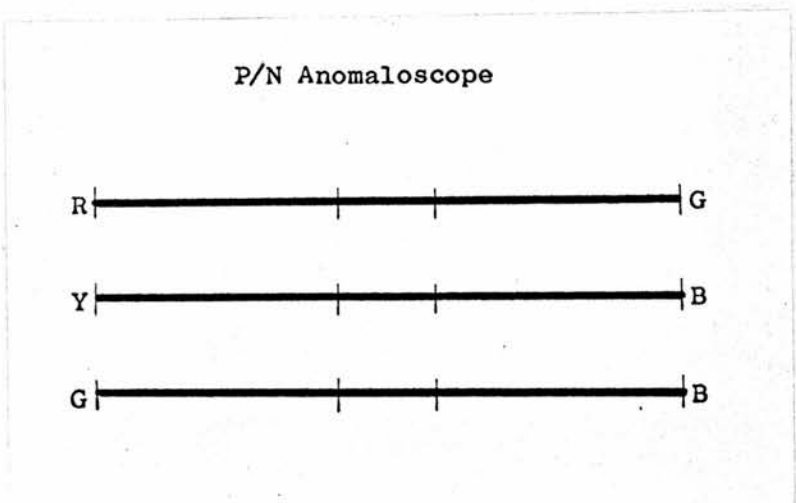


Figure 125 Retinitis Pigmentosa

attached to the early and late cross-over times. Certainly the early cross-over time is associated with only blue/green and yellow/blue losses, whereas the late cross-overs have additional red/green losses. Whether they are representative of qualitatively different types of functional change or simply different stages of degeneration is not known. However it seems more likely from the evidence in Figs. 119 to 122 that two distinct types of early change are present. The peripheral collapse of the scotopic system would appear to be an early indication of degenerating vision as is commonly supposed. As Fig. 122 shows, colour vision on the 100 hue test is good when the scotopic system is already markedly affected. The value of colour vision tests can be seen in Fig. 124 and 125 where although dark adaptation losses are of the same type and degree, one individual maintains some red/green discrimination but the other has achromatic vision.

3. Relation between Structure and Function

(i) Method

For the purposes of this analysis the structural regions M, Fovea, Parafovea, Perifovea, foveal surround, have been correlated with the visual function tests. See Fig. 118 for an explanation of these areas. All the visual function tests listed in Table XXIX are included in the analysis.

(ii) Results/

T A B L E XXXI

STRUCTURE

FUNCTION	M	FOV	PARAFOV.	PERIF.	FSUR
EOG	-	-	-	-	-
ERG	-	-	-	.01	-
Visual Acuity	.01	.01	.01	.01	.01
Ishihara	-	-	-	-	-
100 hue A	.05	-	-	-	-
B	.01	-	-	-	-
C	-	-	-	.05	-
D	.01	-	-	-	.05
Total	.05	-	-	.05	-
Increment Threshold	.05	.05	-	-	.05
DAB4	-	-	-	.05	-
DAY4	-	-	.05	.01	-
DAB20	-	-	-	.05	-
DAY20	-	-	.05	.01	-
Cross over	-	-	-	.05	-
RGMR	.01	-	-	-	-
RGMP	.01	-	-	-	-
YBMR	-	-	.01	.01	-
YBMP	-	-	.05	.05	-
BGMR	-	-	-	.01	-
BGMP	-	-	-	.05	-

Probability levels at which correlations between function and structure are significant. Dashed lines indicate no significant correlation.

(ii) Results

The significance of the structural and functional relationships was assessed by contingency coefficients. The results are presented in Table XXXI, where the probability levels at which significance is reached are listed. Dashed lines indicate no significant association. It should be remembered that as over 100 comparisons have been carried out in this Table, one would expect to find five significant associations by chance at the .05 probability level and one significant result by chance at the .01 probability level. In addition the structural variables 'Fovea' and 'Foveal surround' make use of overlapping fundal areas, so that they are not independent structural variables (four elements in 'Foveal surround' are included in 'Fovea'). Consequently the two structural variables correlate in a similar way with any of the functional tests.

(iii) Discussion

With these reservations in mind there are several interesting correlations in the Table. Firstly neither of the electrodiagnostic measures reflects the degree of structural abnormality in a central fundal region. Of the areas considered, only the structure of the perifovea is associated with the E.R.G. The lack of association emphasises once more the fact that the electrodiagnostic measures represent gross activity/

activity of the whole retinal area, whereas structural features have been considered for only a central region. The psychophysical tests might be expected to give a better indication of the relation between function and structure, as they involve those retinal areas in which structure has been assessed.

The visual acuity results correlate significantly with abnormalities in all five fundus regions. It is the only visual function test to do this. The foveal increment threshold correlates with structural abnormalities in region M and Fovea but not with more peripheral regions. On the other hand the 100 hue test correlates with structural features in the two extreme areas, M and Parafovea, but not with those in the intermediate zones. Both the photopic and the scotopic portions of the dark adaptation curve correlate significantly with abnormalities in the parafovea and perifovea but not with abnormalities in the central region. (It should be remembered that the criteria for 'seeing' in dark adaptation is that light is visible anywhere within a 10° area centred on the fovea. It cannot be assumed that the subject saw a full circular test patch at points above threshold).

Perhaps the most interesting results are revealed by the anomaloscope. The matching range and mid-matching point of the red/green equation correlate significantly with structural abnormalities in the central region, but do not correlate with structural abnormalities in the/

the more peripheral zones. This situation is almost completely reversed on the yellow/blue and blue/green equations. Here the strucutre of the periphery correlates with these functional measures, but the structure of the central area does not. Furthermore the fundal areas correlating with yellow/blue and blue/green discrimination are those correlating with dark adaptation results.

What hypothesis could be proposed to account for these findings?

It will be recalled in sections 1 and 2 that two hypotheses regarding changes in structure and in visual function in retinitis pigmentosa have been supported (but not confirmed) by the evidence in each section. The first hypothesis suggested a change in structure which began in the peripheral zones and moved towards the fovea. The second hypothesis suggested a sequence of colour vision defects in which blue/green vision was affected at an early stage, and red/green vision at a later stage of the disease. On the basis of these hypotheses, the correlations between structure and function show that the early indications of structural change are associated with the early indications of functional change. Similarly, the later indications of structural change are associated with the later indications of functional change. The correlations appear to give further evidence for the support and for the inter-/

inter-relation of the two hypotheses.

However, these findings should not be taken to imply that the functional and structural changes are occurring at the same rate, or at the same time, in areas where significant correlations are present. All that can be said, is that normal structure is associated with normal function, and abnormal structure with abnormal function in the peculiar way that is outlined above. Furthermore Tables XXVIII and XXIX show that a greater proportion of individuals have abnormal function than have abnormal structure in any particular area. For any one fundal area there are a maximum of 79% of abnormalities on Fig. 118 and 83% of abnormalities if the equatorial region is included. On the other hand 95% of patients have abnormal blue/green matching ranges and 85% have abnormal red/green matching ranges. As all the patients have abnormal structure in some fundal region (in order to be included in the sample) it follows for instance that there must be at least 17% of patients whose abnormal structure does not begin in the equatorial region. Either these individuals are representative of a different species of retinitis pigmentosa, or the hypothesis of structural change might be qualified to the effect that whenever structural changes have occurred the subsequent changes are in a centripetal direction. However, until the rates of structural change are known it is not possible to clarify/

clarify this further.

It is apparent that in the foveal region only 50% of patients have abnormal structure, but 95% of patients have abnormal function. The minimum percentage of the normal function category for any test is 75%, (for visual acuity). All patients with structural abnormalities in this area have detectable functional abnormalities. It is clear, therefore, that functional changes precede structural changes in the foveal region. The lack of correlation between the blue/green matching range and foveal structural abnormalities is explained by the fact that abnormal matching ranges are associated with both normal and abnormal structure in this region.

Blue/green discrimination remains the most sensitive test of visual abnormality, but red/green discrimination gives the best indication of structural changes in the foveal region. Although the increment thresholds is a sensitive test of visual function with 90% of patients outwith normal limits, the test does not correlate as strongly with foveal structural changes as do visual acuity and the red/green anomaloscope equation.

(iv) Conclusions

Structural changes within an area of 20° diameter about the fovea were analysed. There was a significantly greater proportion of abnormal structure in the peripheral zones of this region than in the central zone. There is no indication of increased abnormality in either one/

one of the temporal, nasal, upper or lower quadrants. Furthermore the difference in abnormal structure between centre and periphery is symmetrically distributed about the foveal region. If the rate of degeneration of structure is different in different retinal areas these findings are in keeping with a hypothesis of sequential change in abnormalities from the peripheral to the foveal regions of the 20^{o} area.

The functional results show gross abnormalities on all tests with blue/green discrimination most affected. 80% of cases have already reached the dichromatic stage of a blue/green colour defect. Scotopic losses are more extensive than photopic losses in the sample. In general the psychophysical tests correlate highly with each other but there are relatively few significant correlations between psychophysical and electrodiagnostic measures. An analysis of the anomaloscope equations supports the hypothesis that blue/green defects occur at an early stage in the disease with red/green defects occurring at a later stage.

A comparison of structural and functional changes shows that functional abnormalities are more extensive than structural abnormalities in the foveal region. This applies to any measure of visual function included in the test battery. The percentage of cases with functional abnormalities ranges from 75% on visual acuity and on the 100 hue test, to 95% on the blue/green matching range./

range. The structural abnormalities are present in 50% of cases. Correlations between function and structure indicate that Snellen visual acuity and the 100 hue test correlate with structural changes in both the central and peripheral regions of a 20^{o} circle centred on the fovea. On the other hand blue/green discrimination and dark adaptation are only significantly associated with structural changes in the peripheral zones of this region, and red/green colour discrimination and the foveal differential threshold are only significantly correlated with structural changes in the central zones of this circle around the fixation point.

d.) MISCELLANEOUS

This section consists of patients with a variety of conditions. Each subgroup is presented in note form. Where appropriate a brief discussion of general results is given. Otherwise individual cases are presented. This section focusses on the pattern of scores across different tests as well as the general findings for any subgroup.

1. Colloid Bodies

Visual function results on patients with colloid bodies in the macular region are reported. Of the original sample selected for this study, several patients were subsequently discovered to have additional clinical features (e.g. glaucoma or pigmentary disturbance). These/

These patients were removed from the sample, leaving a total of 23 eyes in which the appearance of colloid bodies was the only clinical symptom.

Background

There appear to be mixed findings on visual function in this condition. Dark adaptation is described as normal in some cases (FORNI and BABEL, 1962; DEUTMAN, 1971); slightly abnormal in others (in which the rate of reaching the normal rod and cone thresholds is delayed, KRILL and KLEIN, 1965); and markedly abnormal in others PAJTAS (1950, 1957). Similarly the E.O.G. and E.R.G. results show both normal and abnormal function which may be related to the extent of retinal involvement in different patients (FARKAS et al, 1971).

Colour vision is reported as normal until the foveal area is affected (DEUTMAN, 1971), with a subsequent loss of sensitivity to red. Following an initial red/green dyschromatopsia, a yellow/blue dyschromatopsia is described at an advanced stage of the disease. On the other hand FRANCESCHETTI et al (1963) described a yellow/blue dyschromatopsia as most characteristic of the disease, which precedes other visual losses.

It is clear that such findings are contradictory only if the same condition is assumed to hold for all patients. The usefulness of visual function in this situation may be to point to several different entities subsumed under the same name./

name.

Method

Patients were tested on the following psychophysical tests:- Ishihara and AOHRR Pseudo Isochromatic plates, 100 hue test, Pickford Nicholson Anomaloscope, Static Perimetry, Dark Adaptation, Photopic luminosity function.

Results

1. Pseudo Ishochromatic plates:- 91% of patients were normal on the Ishihara and AOHRR tests (i.e. made less than four mistakes).
2. Visual Acuity:- 86% of patients had normal Snellen acuity.
3. 100 hue test:- 74% of patients had error scores within normal limits (All 26% of the abnormal profiles were anarchic, but 12% of the normal profiles had tritan axes).
4. Photopic luminosity function:- 65% of the patients were able to carry out this test. All had spectral sensitivity curves which were within the normal limits.
5. Pickford Nicholson Anomaloscope:- Red/green equation 52% of patients had normal discrimination, and normal mixture ratios. A further 4% had normal discrimination and an abnormal mixture ratio, with a shift in the mid-matching point towards the red. The remaining 44% of cases with abnormal discrimination consisted of 40% in which there was a significant/

significant shift in the mid-matching point towards the red, and 4% in which the mixture ratio was normal.

Yellow/blue equation:- only 9% of cases had normal colour discrimination. A breakdown of the remaining 91% with abnormal matching ranges was as follows. 18% had reached the dichromatic stage on this equation. The remaining 73% had extended matching ranges of which 61% were symmetrical about the mid-matching point and 12% were shifted towards the blue end of the spectrum.

Blue/green equation:- only 9% of cases had normal colour discrimination. The remaining 91% with abnormal matching ranges were divided as follows. 33% had reached the dichromatic stage on the equation. The remaining 58% had extended matching ranges, of which 21% were symmetrical about the mid-matching point; 12% were shifted towards the green, and 25% were shifted towards the blue end of the spectrum.

6. Foveal differential threshold:- 71% of patients had normal thresholds.

7. Dark adaptation:- 56% of patients had abnormal rod thresholds after 20 minutes following preadaptation. Of these, 30% were markedly abnormal (thresholds raised over 2 log units) and 26% were slightly abnormal (thresholds raised less than 1 log unit)./

unit). Most cross-over times were within normal limits. However, 13% had significantly late cross-overs and 9% had significantly early cross-overs.

Discussion

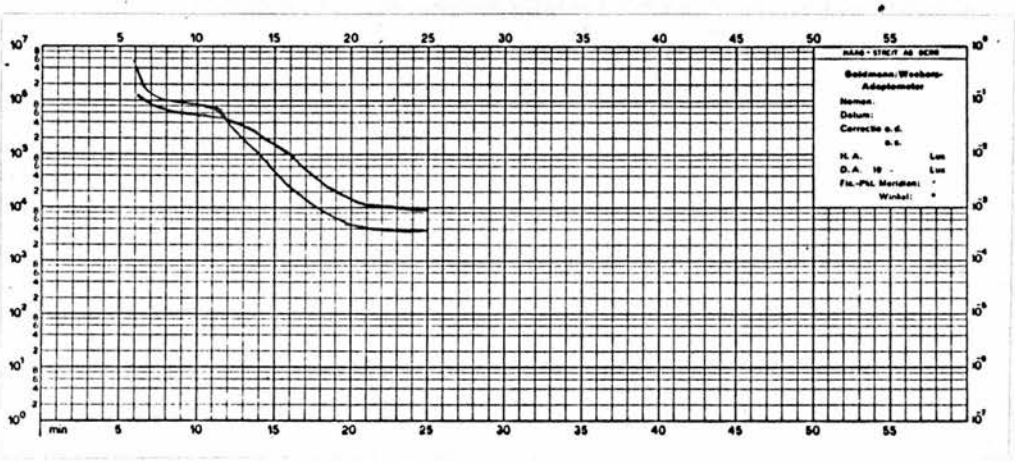
General group results will be considered first followed by the presentation of a sample of individual results.

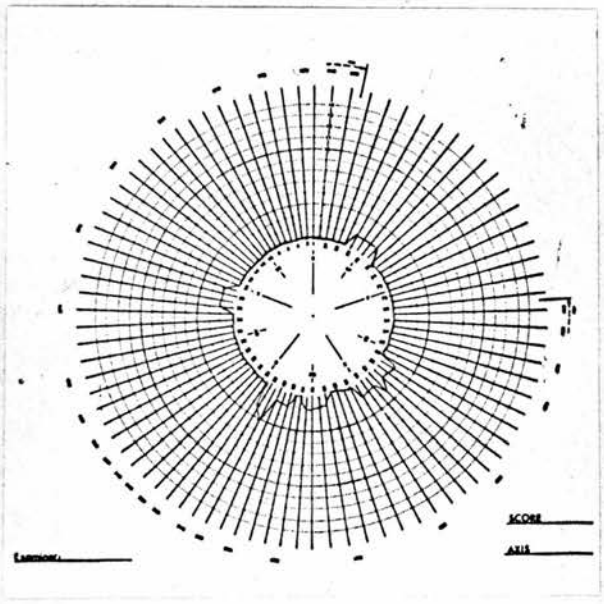
There are two notable features in the colour vision data. Firstly, the predominant colour loss is along the yellow/blue and blue/green axes. Secondly, where red/green losses do occur, they are nearly always accompanied by a shift in the mid-matching point towards the red. The first question which arises is the relationship between the two types of defect. In this respect there were several instances where red/green defects accompanied yellow/blue defects. In fact in all cases where a red/green dyschromatopsia was present there were concomitant losses on either the yellow/blue or blue/green equations. (The yellow/blue and blue/green measures were significantly related so that either both were normal, or both were abnormal). However in 35% of cases there existed either yellow/blue or blue/green defects without concomitant red/green losses. This evidence suggests that the yellow/blue dyschromatopsia is an earlier symptom than the red/green dyschromatopsia which is in agreement with FRANCESCHETTI et al (1963) and contrary to DEUTMAN (1971)/

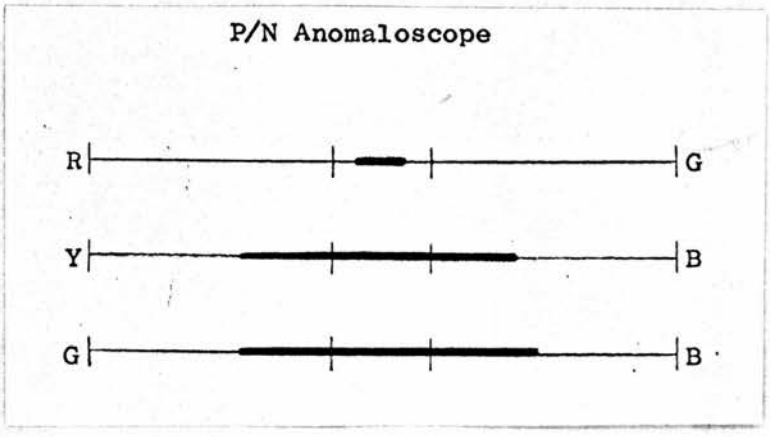
(1971) and KRILL and KLEIN (1965). On the other hand the red/green dyschromatopsia, when it did occur, was almost invariably accompanied by a shift in the mid-matching point towards the red as DEUTMANN (1971) reports. All the patients in the group who had reached the dichromatic stage of yellow/blue deficiency had extended red/green matching ranges.

A comparison of the data from different colour vision tests illustrated once more the peculiar nature of colour vision measurement. Although 74% of patients had 'normal colour vision' on the 100 hue test, only 9% of patients had 'normal colour vision' on the Pickford Nicholson anomaloscope. The fact that the tests tended to correlate with each other (when they were linked by the common measure of deteriorating vision) should not be allowed to obscure this. As an example of the relationship between the tests, it was found that all the cases with abnormal 100 hue error scores had abnormal matching ranges on all three anomaloscope equations. However the converse did not hold, as there were individuals with abnormal anomaloscope matching ranges but normal 100 hue profiles.

The dark adaptation results fell into three fairly distinct categories, with 44% of patients having normal rod thresholds; 26% having slightly abnormal thresholds; and 30% having markedly abnormal thresholds. There was no relationship between colour vision results and dark/







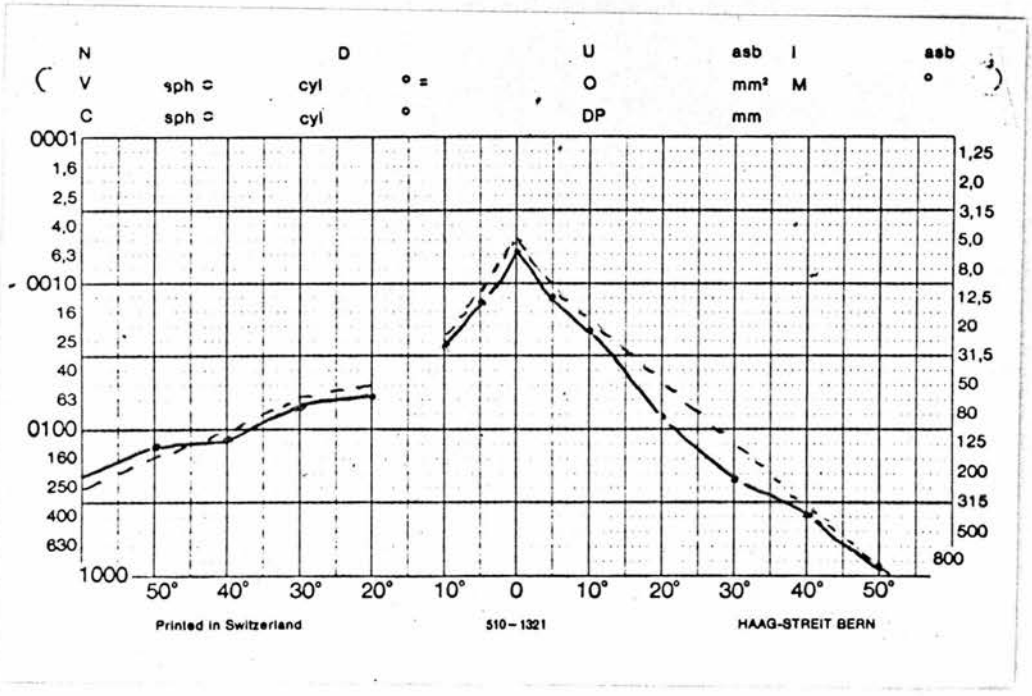
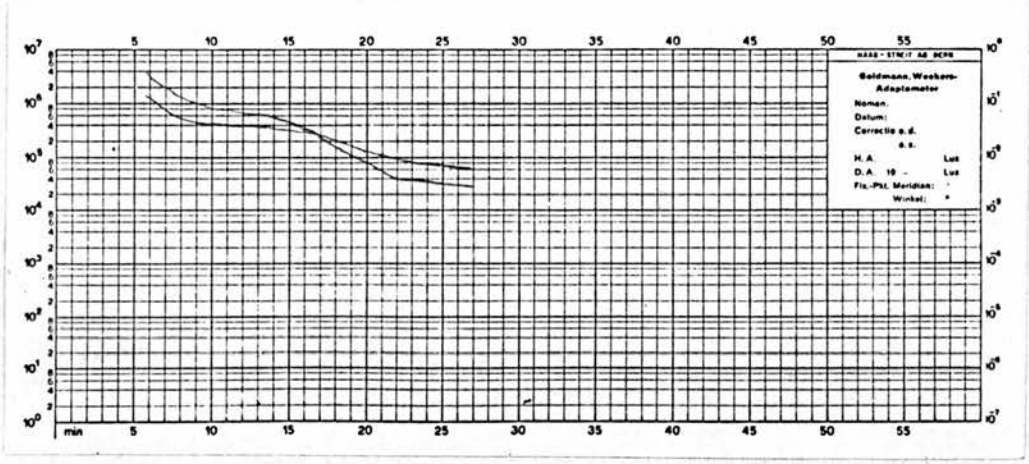
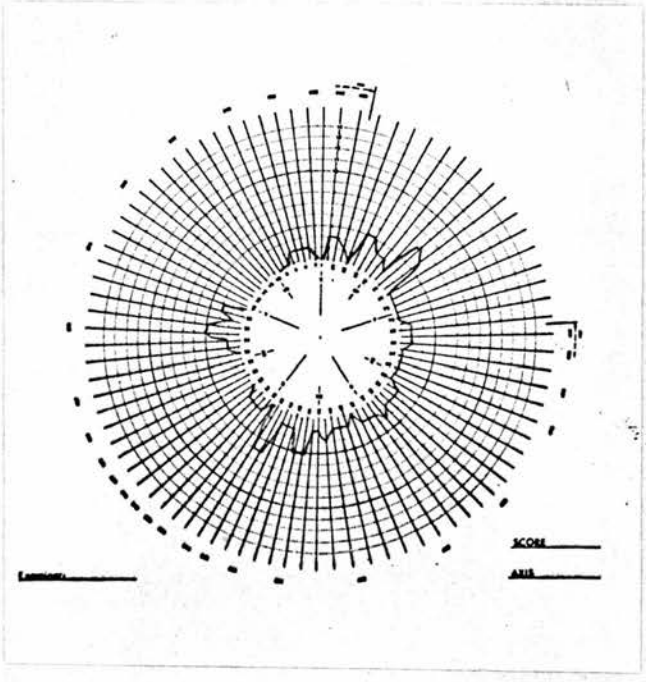


Figure 126 Colloid Bodies - Early Anomaloscopic Losses





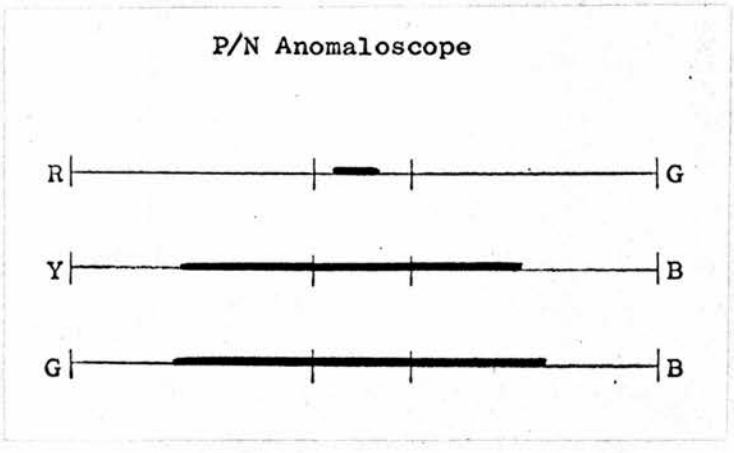
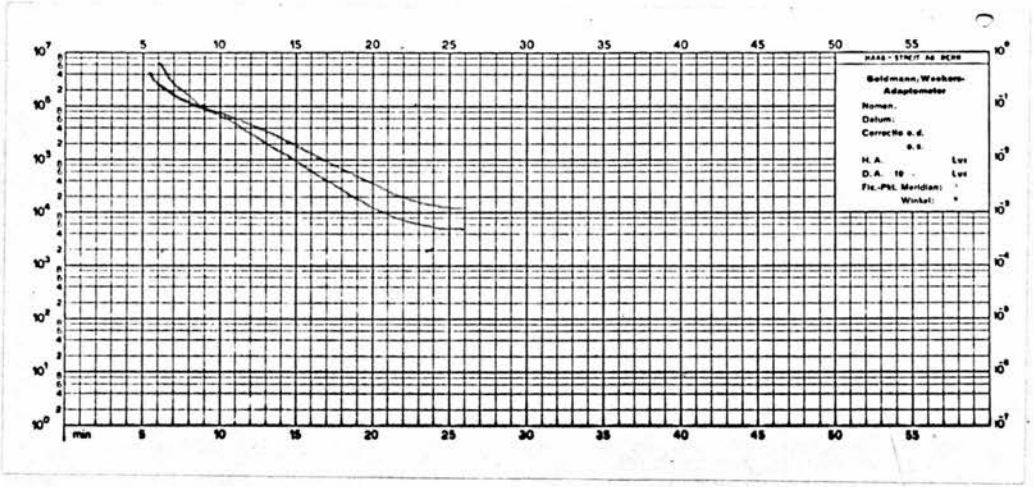
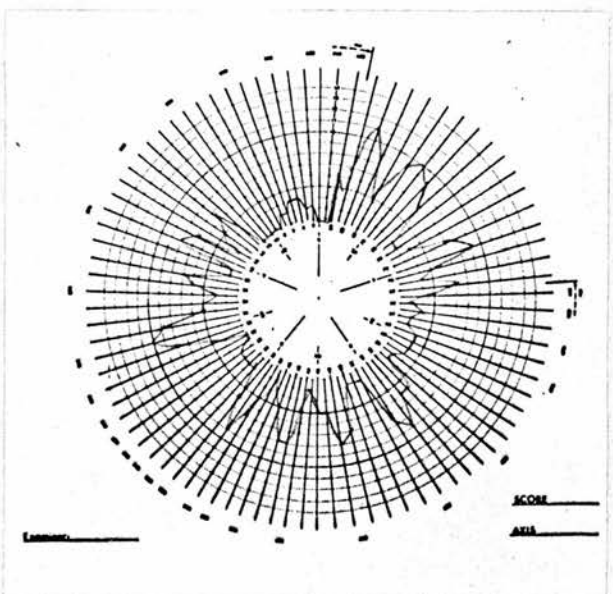


Figure 127 Colloid Bodies

dark adaptation results. For instance in the subgroup with normal 100 hue profiles there were equal numbers in the three dark adaptation categories. There was also one individual with an abnormal 100 hue score and a normal dark adaptation threshold. Similarly, knowledge of the red/green matching range gave no indication of the likely dark adaptation results, and all possible combinations of normals and abnormals on the two tests occurred. Most of the yellow/blue matching ranges were abnormal, but the dark adaptation results were again equally divided in all three categories. The photopic luminosity function did not appear to discriminate between the patients irrespective of their performance on other tests.

Some examples of typical individual results are now presented. Fig.126 illustrates a case where all the results are normal with the exception of the anomaloscope yellow/blue and blue/green equations. This may represent the earliest type of change in the group. Fig. 127 also shows good colour discrimination on tests other than the anomaloscope, but there are additional losses in dark adaptation with a significantly late cross-over time. The final dark adapted thresholds fall into the intermediate range. In contrast to Fig.127, Fig. 128 shows that final dark adapted thresholds can be normal but colour vision can be markedly affected. Here both the Ishihara and the 100 hue results are abnormal,/





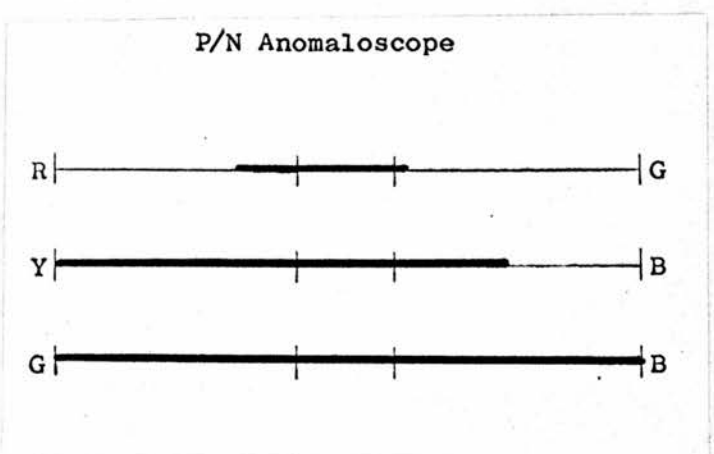
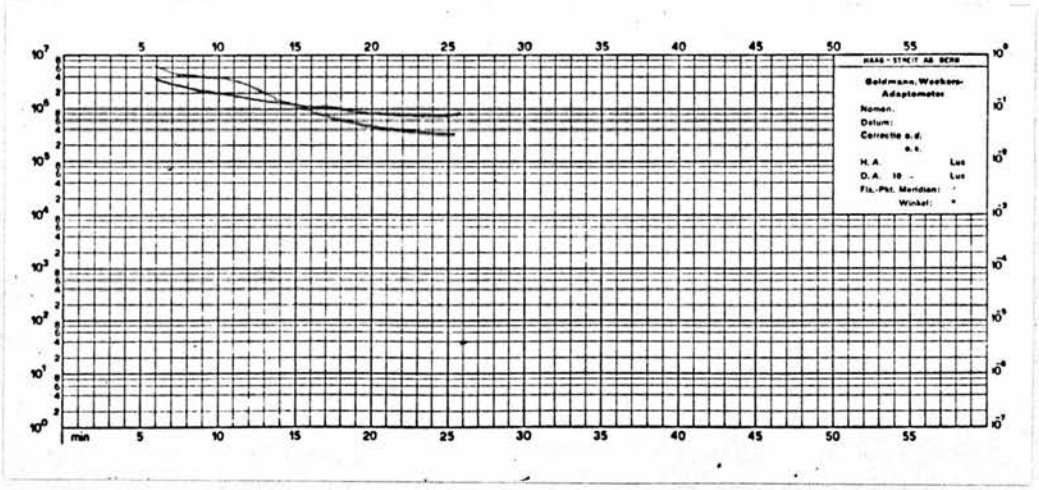
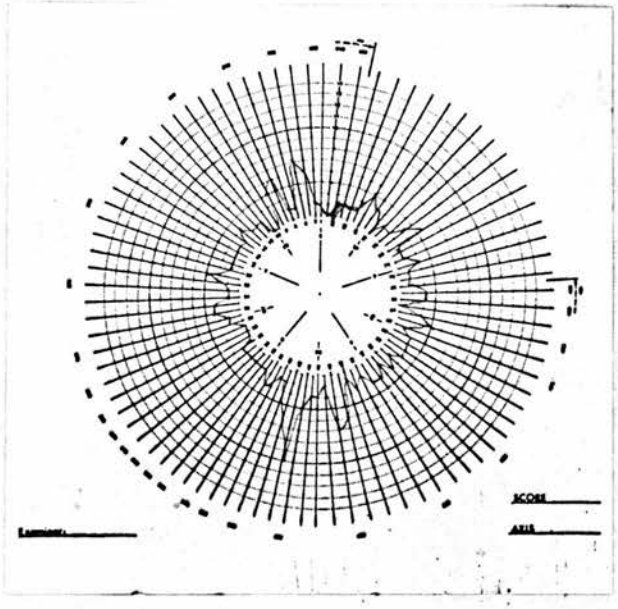


Figure 128 Colloid Bodies





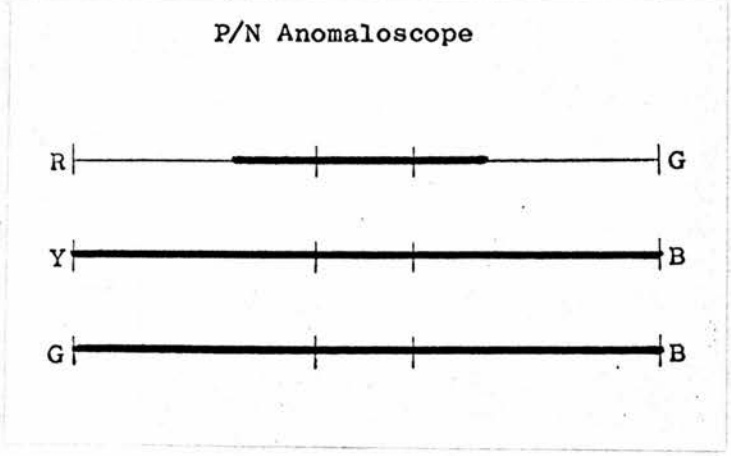


Figure 129 . Colloid Bodies

abnormal, in addition to extended losses appearing on the red/green anomaloscope equation. Note that the blue/green equation has reached the dichromatic stage. The defect in this case appears to be particularly affecting the cones. The early cross-over in dark adaptation, together with the normal rod thresholds, illustrates the tendency for rods to take over function early in the dark adaptation process. Finally Fig. 129 shows an example of markedly abnormal dark adaptation thresholds. Although the 100 hue and Ishihara scores are within normal limits, the anomaloscope does indicate severely impaired colour discrimination which has reached the dichromatic stage on the yellow/blue and blue/green equations and has also affected the red/green equation.

The individual results emphasise the lack of correlation between the tests. Although in general grossly abnormal colour vision is associated with grossly abnormal dark adaptation, there are several intermediate stages where many different combinations occur. The significance of the early or late cross-over times is not known. However, early cross overs only occurred when there was normal scotopic function, and late cross-overs were only associated with abnormal scotopic function. The photopic function could be either normal or abnormal in both cases.

Summary/

Summary

Colour vision is a more sensitive measure of change in this group than either visual acuity or the foveal differential threshold. The results showed a majority of colour vision losses of the yellow/blue and blue/green type. These appeared to be the earliest type of loss in this condition as they occurred without the presence of red/green losses, although red/green losses did not occur without them. When a red/green dyschromatopsia was present, it was associated with a shift in mid-matching point towards the red, indicating a loss in sensitivity to long wavelengths. An extension of the red/green matching range was found in some cases before the yellow/blue and blue/green losses had reached the dichromatic stage. When the latter losses had reached the dichromatic stage, there were always red/green losses beyond the normal limits. The 100 hue test showed normal discrimination profiles in several cases where the anomaloscope indicated abnormal colour vision.

The dark adaptation results fell into three categories, normal; slightly abnormal; grossly abnormal. Little relationship was found between colour vision and dark adaptation data, and normal and abnormal colour vision existed with normal and abnormal dark adaptation. Both early and late cross-over times were found. Early cross-overs were only present when rod function was normal. The general findings are in agreement with/

with FRANCESCHETTI et al (1963). When a red/green dyschromatopsia was present it was of the type described by DEUTMAN (1971) although the sequence of colour vision changes appeared to be the reverse of Deutman's results.

2. Disciform Degeneration of the Macula

Background

A yellow/blue dyschromatopsia appears to be characteristic of this condition. Early reports were by SLOAN (1942), who reported misreadings on the tritan plates of Stilling, and ZANEN (1953) who reported an increase in the foveal thresholds to blue. Subsequently FRANCOIS and VERRIEST (1957) and BOZZONI (1959) reported a yellow/blue dyschromatopsia with the mean confusion axis near that of congenital tritanopia.

In a study of 30 subjects COX (1960) found that 25 had yellow/blue losses while 5 had normal vision. There were also red/green losses when visual acuity was reduced. Similarly VERRIEST (1964) found predominantly yellow/blue losses in 18 subjects. Moderate losses appeared on the red/green equation, with an occasional marked shift in the mid-matching point towards the red. (JACOBSON et al, 1956, found that the E.R.G. was practically absent to red stimuli but normal to white). Colour discrimination was seen as an early sign of visual loss, because it appeared while acuity was normal, and occasionally reached the dichromatic stage before acuity was affected./

affected.

Method

Seventeen eyes were examined on the following psychophysical tests - Ishihara, 100 hue test, Pickford Nicholson Anomaloscope, Static perimetry, Dark adaptation.

Results

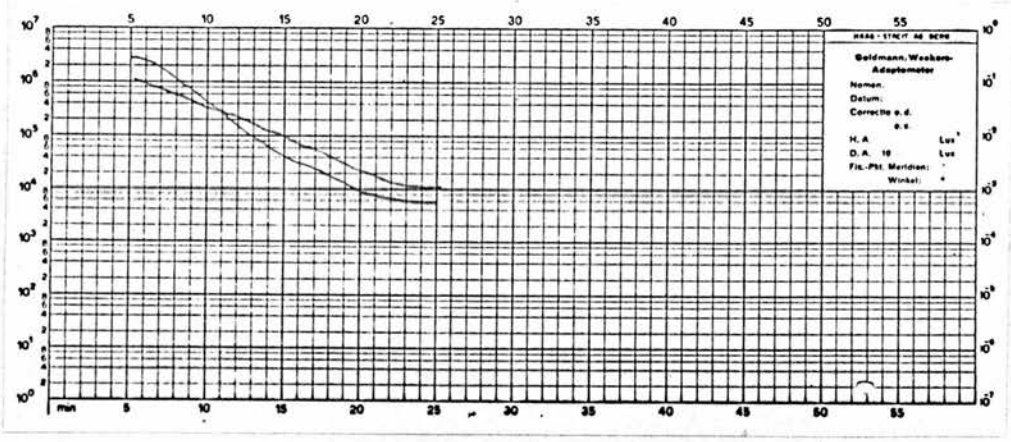
1. Snellen Acuity - 75% of patients had normal Snellen acuity.
2. Pseudo Ishochromatic Plates - 52% of patients had error scores within the normal limits.
3. 100 Hue Test - 35% of patients had error scores within the normal limits. There was no indication of a tritan axis within the normals. Of the 65% with abnormal profiles, 59% were anarchic and 6% had a tritan axis.
4. Pickford Nicholson Anomaloscope - Red/green equation - 35% of patients had normal red/green matching ranges. Among the abnormal proportion there was a majority with shifts in the mid-matching point towards the red. Yellow/blue equation - only 6% of patients were within the normal limits. Most matching ranges extended to the yellow limit of the equation. 12% of patients had reached the dichromatic stage. Blue/green equation - All patients in the group had abnormal matching ranges and 18% of patients had reached the dichromatic stage. The majority of extended matching ranges/

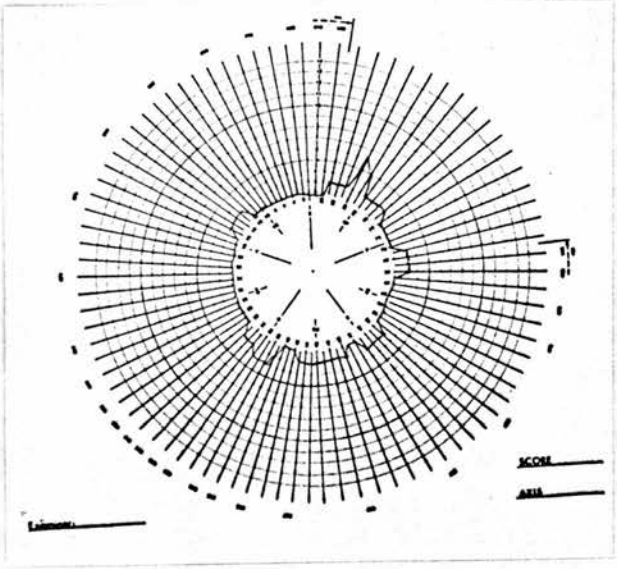
ranges were symmetrical about the mid-matching point.

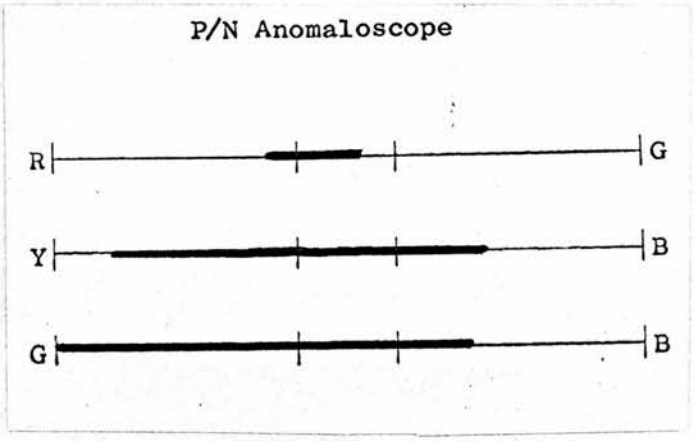
5. Foveal Differential Threshold - 59% of patients were within the normal limits.
6. Dark Adaptation - 52% of patients had normal dark adaptation curves. In the final scotopic thresholds there was a range of abnormalities up to 2 log units beyond the normal level.

Discussion

As all the blue/green matching ranges are abnormal, while only 65% of the red/green matching ranges are abnormal, the predominant colour defect in this condition may be considered to be of the blue/green type. The yellow/blue defect was again closely related to blue/green so that in only 6% of cases the yellow/blue discrimination was normal but the blue/green discrimination was abnormal. Colour vision appeared to be more sensitive than either the acuity or foveal differential threshold measures. In agreement with VERRIEST (1964) two cases in the group had reached the dichromatic stage of blue/green deterioration while the acuity was normal. Although COX (1960) reported the presence of red/green losses when visual acuity was reduced, there were instances in the present population of red/green losses preceding acuity changes. Colour vision also appeared to be more sensitive than dark adaptation, suggesting that colour vision changes were the earliest sign of deteriorating/







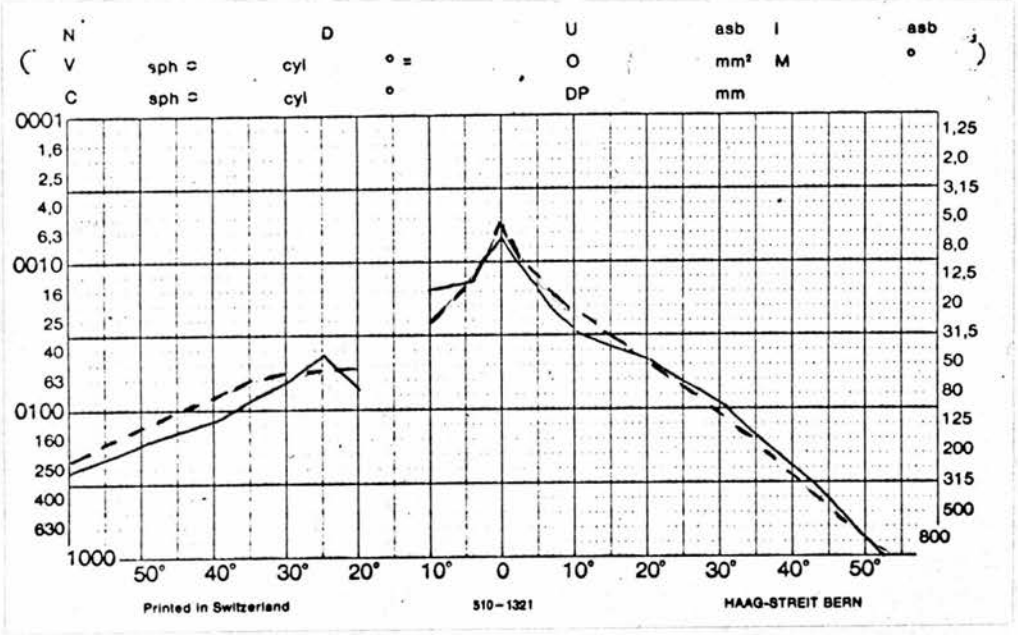
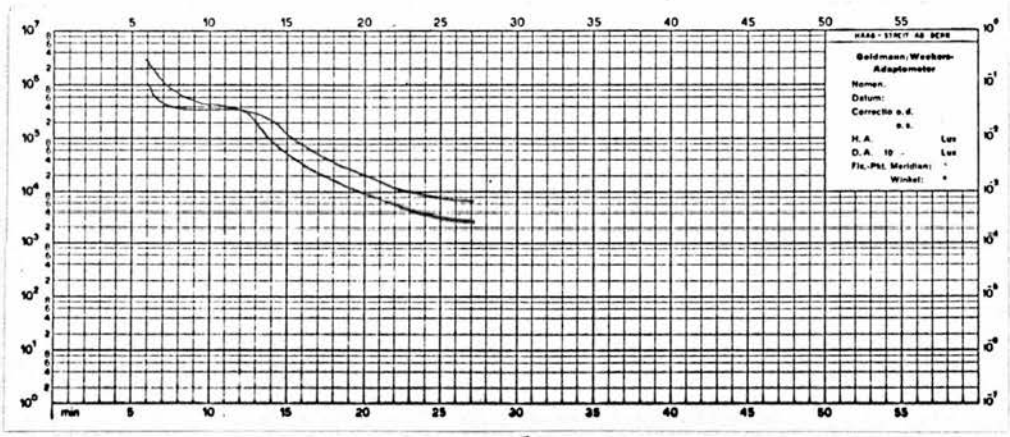
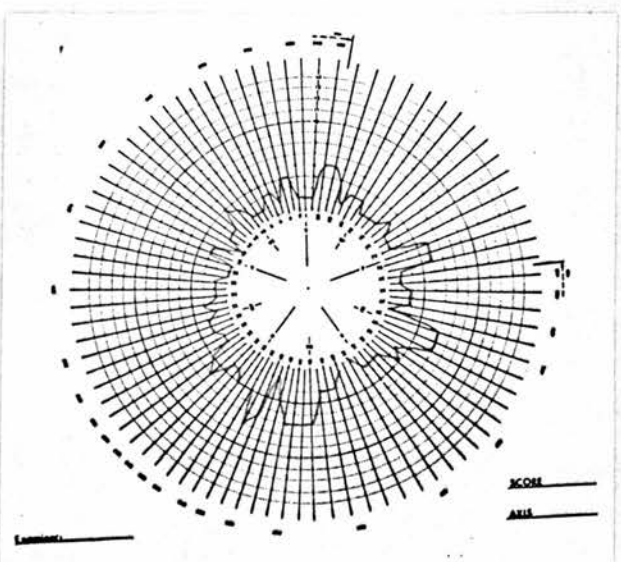
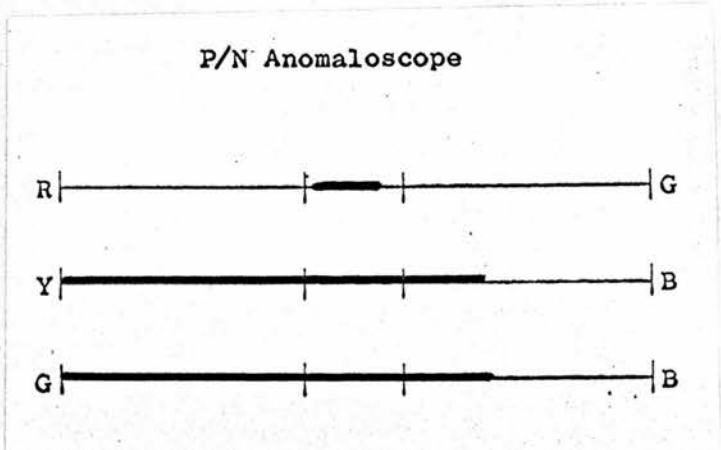


Figure 130 Disciform Degeneration







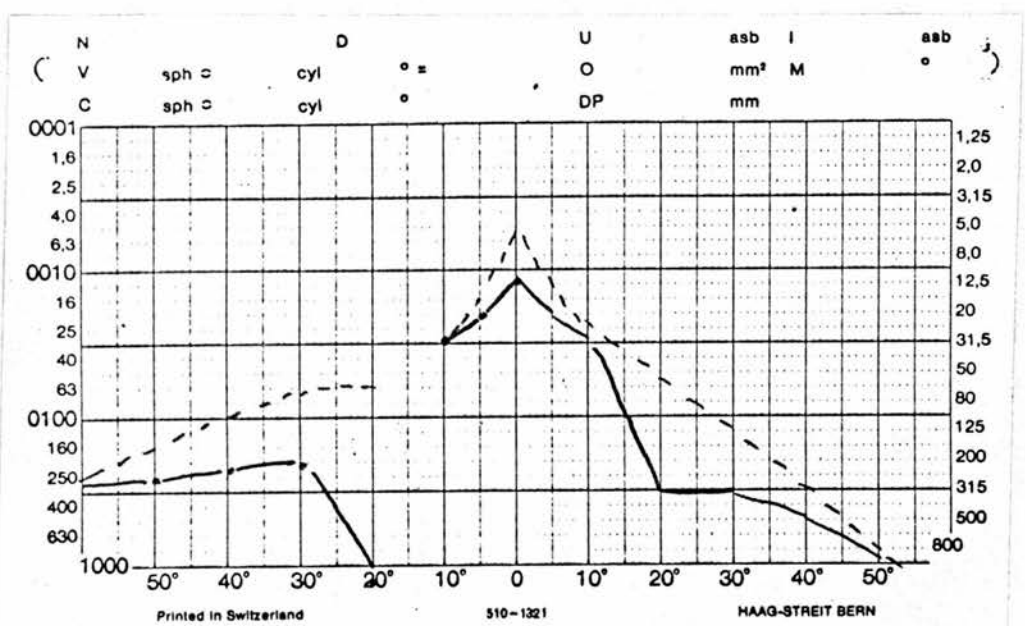
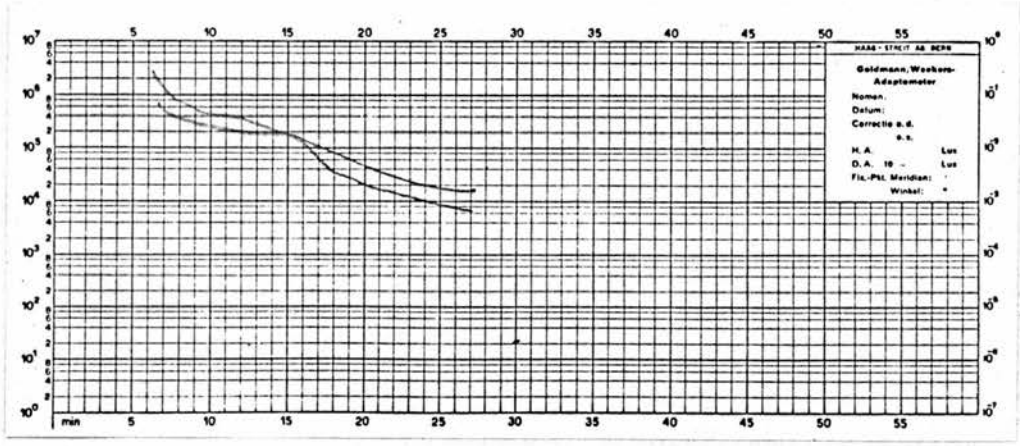
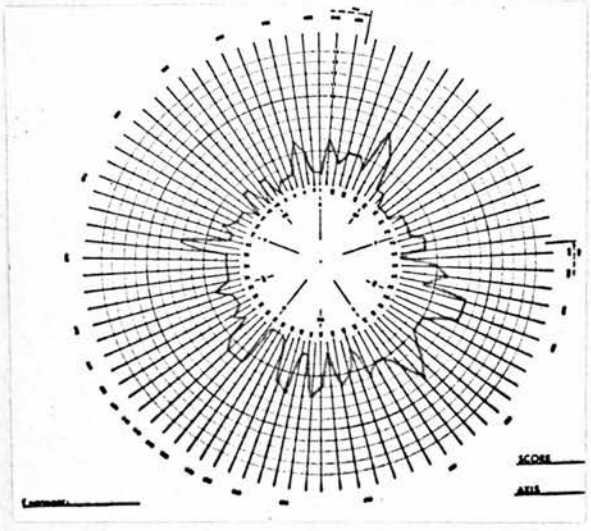
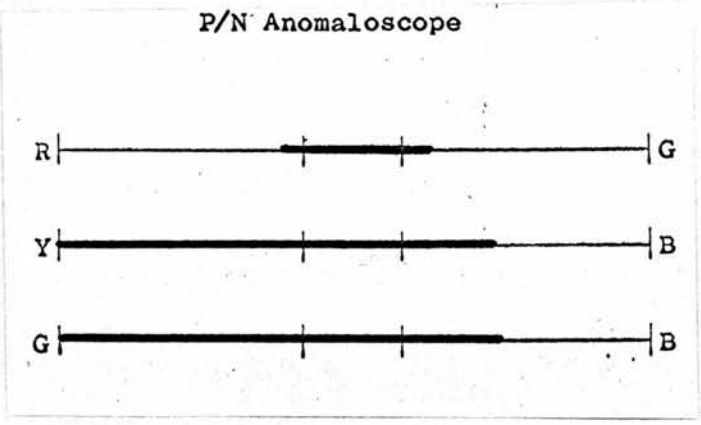


Figure 131 Disciform Degeneration







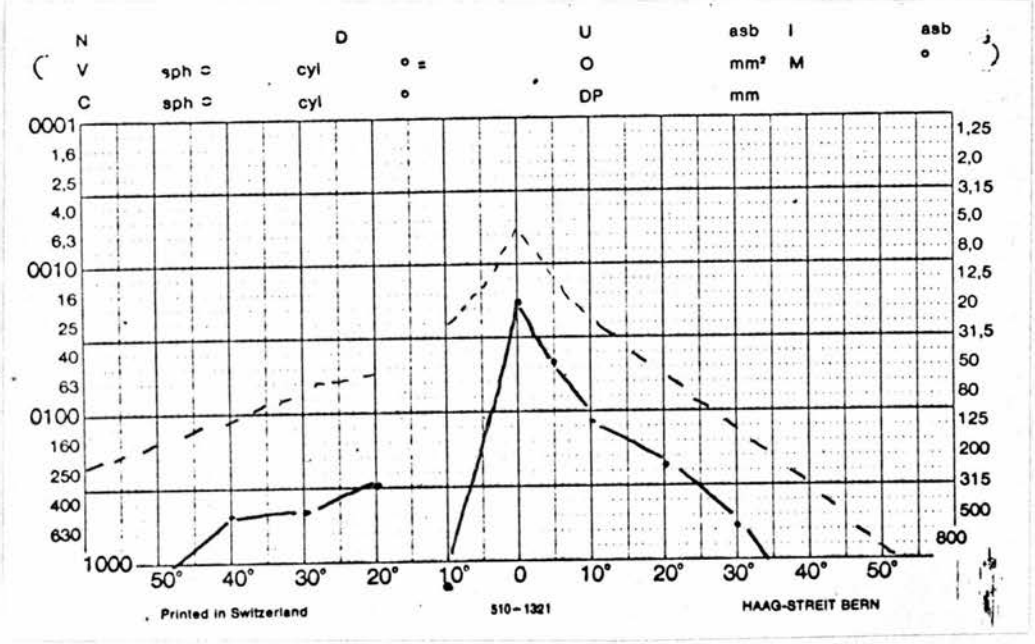
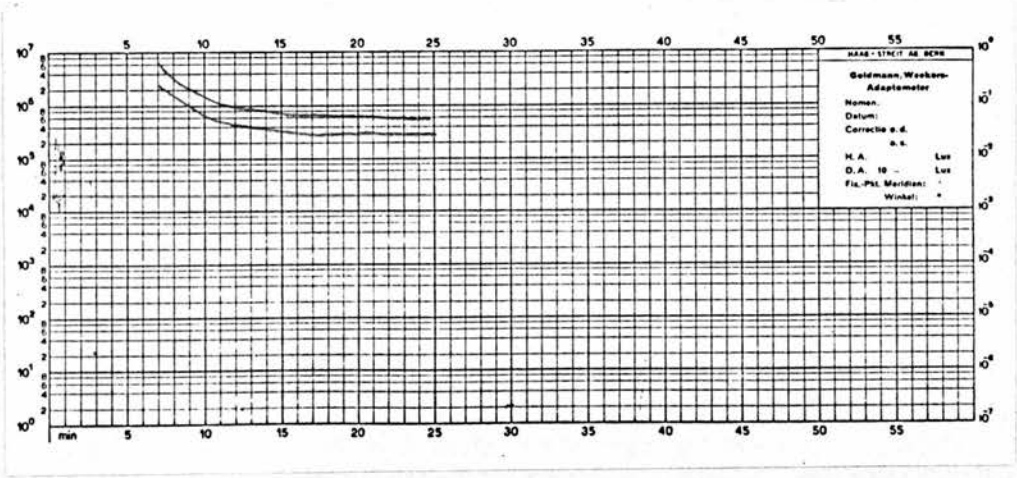
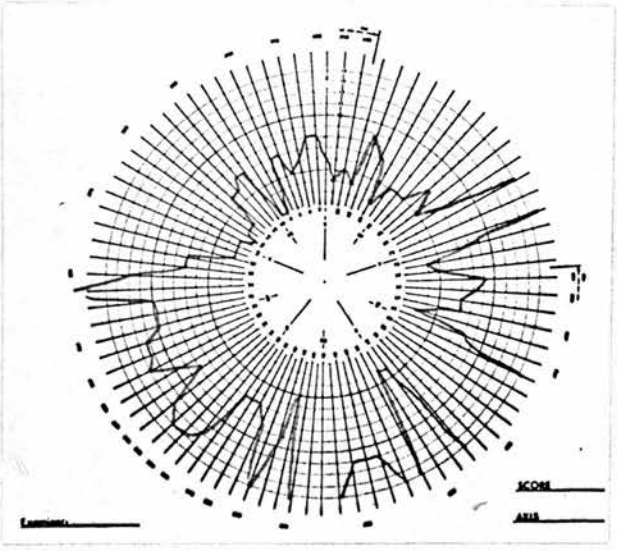
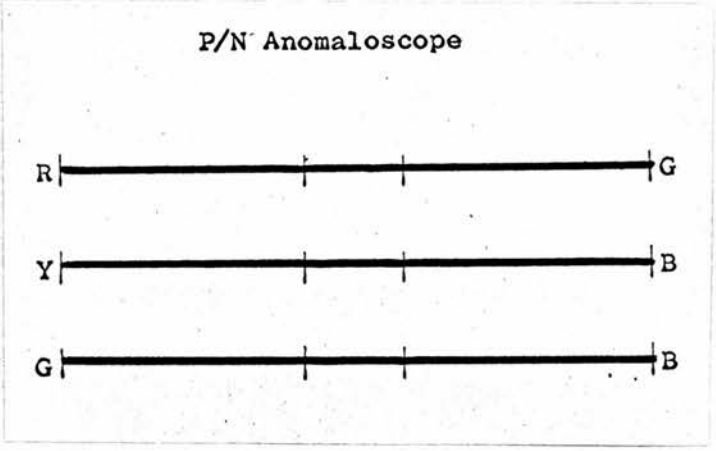


Figure 132 Disciform Degeneration







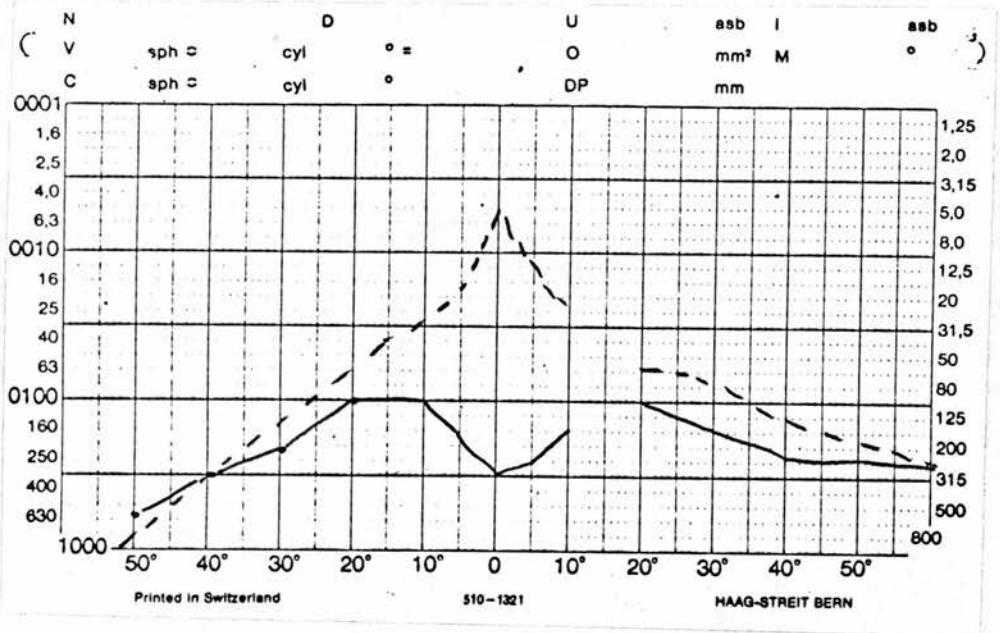


Figure 133 Disciform Degeneration

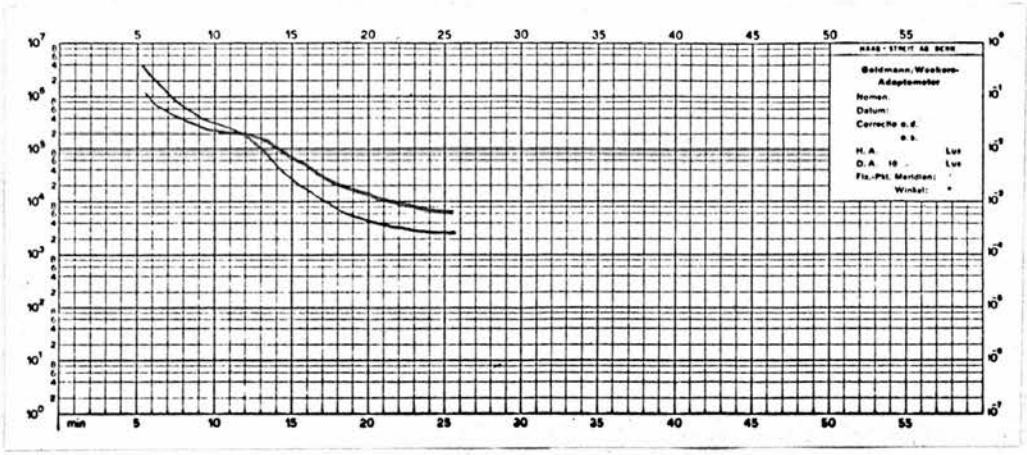
deteriorating vision.

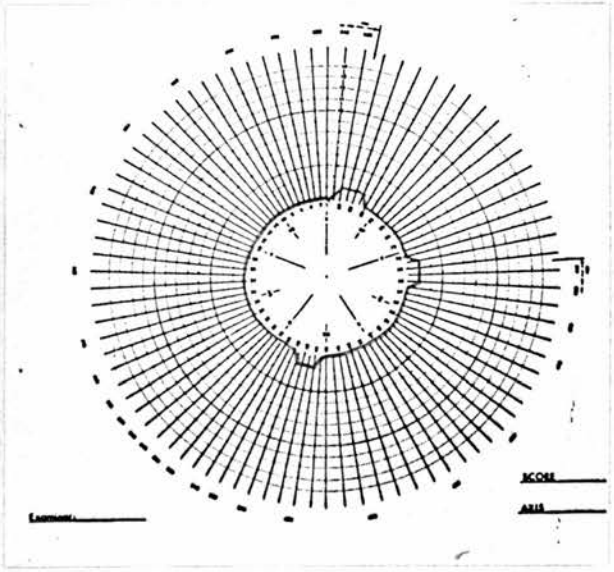
Of the individual cases Fig. 130 shows an example of normal visual function on all but the anomaloscope, where the yellow/blue and blue/green equations have extended matching ranges, and the red/green equation is already shifted towards the red. Fig. 131 and 132 are both instances where the static perimetric profile shows suppression in the retinal periphery. In Fig. 131 the dark adaptation result is normal in all respects. However in Fig. 132 , in which the perimetry losses are more extensive, the dark adaptation result already shows signs of a general raising of thresholds and a late cross-over time. The 100 hue results in both cases are the same (i.e. both anarchic and just outside the normal limit). The anomaloscope losses are also similar in both cases. However additional red/green losses are apparent in Fig. 132 .

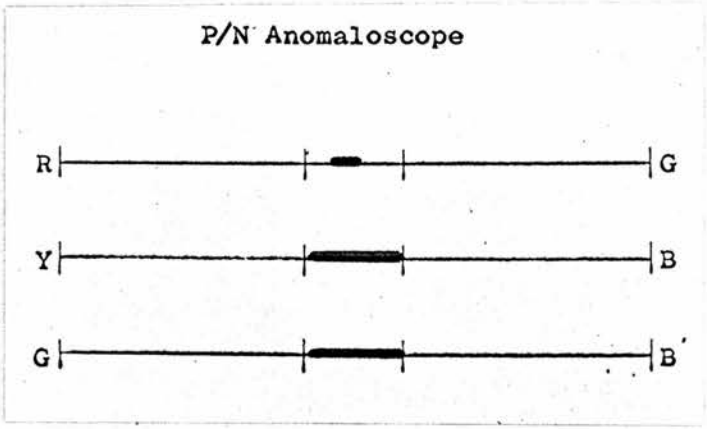
Fig. 133 is an example of a case where there are extensive losses on most tests. The collapse of central vision is particularly apparent on static perimetry, where peripheral thresholds are normal. The 100 hue results indicated little colour discrimination and all anomaloscope equations had reached a dichromatic level. The dark adaptation results showed abnormal thresholds with no cross-over.

Summary

The visual function results suggest that blue/green/







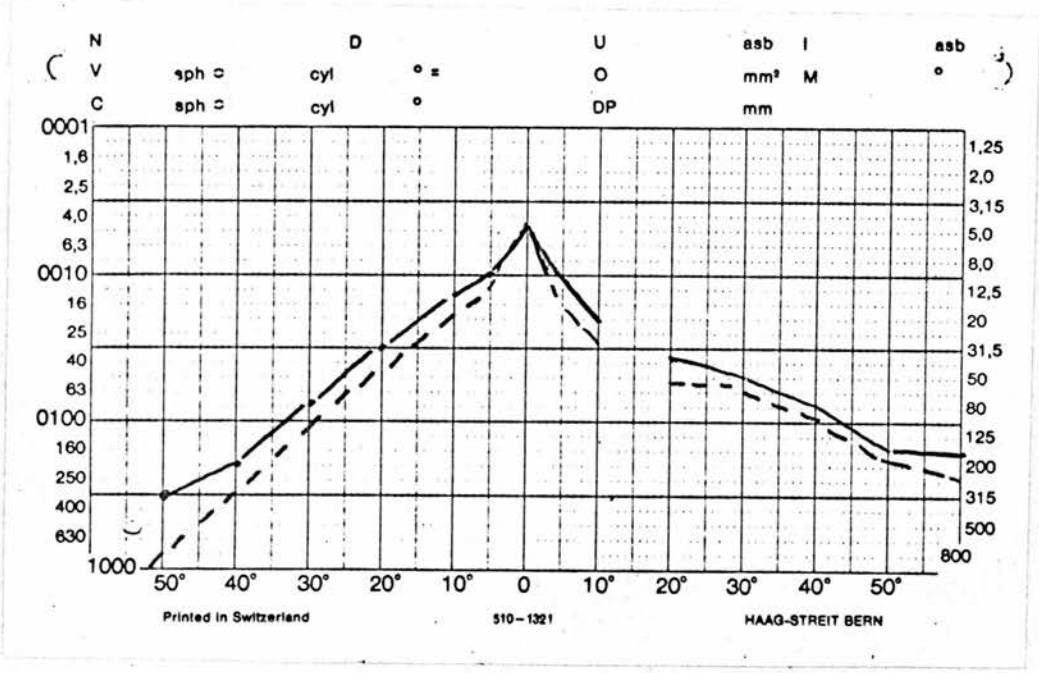


Figure 134 Macular Hole

green losses are one of the earliest indications of visual loss. However the red/green losses are more extensive than those suggested by previous authors and would appear to precede visual acuity changes. A majority of red/green losses included shifts in the mid-matching point towards the red. The colour vision results appeared to be more sensitive than dark adaptation data, in which a wide range of scotopic thresholds were found. If transition points occurred, they were at either normal or at late times following preadaptation. The results are in general agreement with previous findings and indicate that colour vision is a sensitive index of visual change.

3. Macular Hole

Two patients with foveal holes were tested on the test battery.

Results

Both patients were found to have excellent vision on all tests. The results of one patient is shown in Fig. 134. Note the normality of all tests. The only notable feature is the extension of the yellow/blue and blue/green matching ranges, although both remain just within the normal limits. Although one patient complained of adaptational problems, there was no indication of visual loss on static perimetry or dark adaptation.

4. Congenital Nyctalopia

Background/

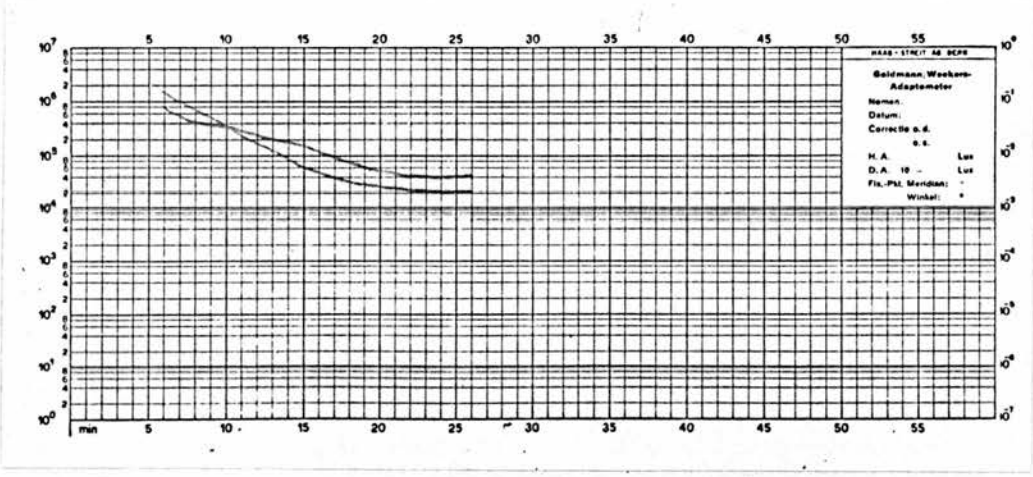
Background

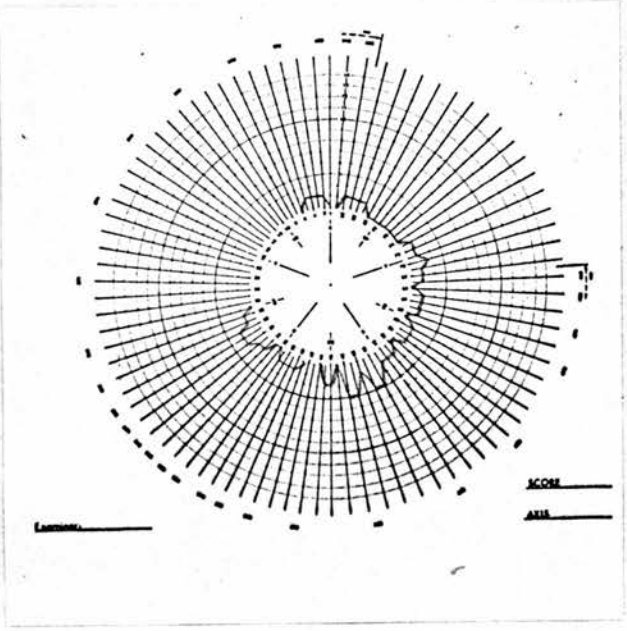
The photopic function as measured by visual acuity, visual fields, the photopic luminosity curve and the E.R.G., are considered normal (VERRIEST, 1964) and colour vision results are frequently normal (GOODMAN and BORSCHEIN, 1957; FRANCESCHETTI, 1958). However colour vision defects of the tritanopic type are reported by ARMINGTON and SCHWAB (1954), and of the tetartan type by VERRIEST et al (1956).

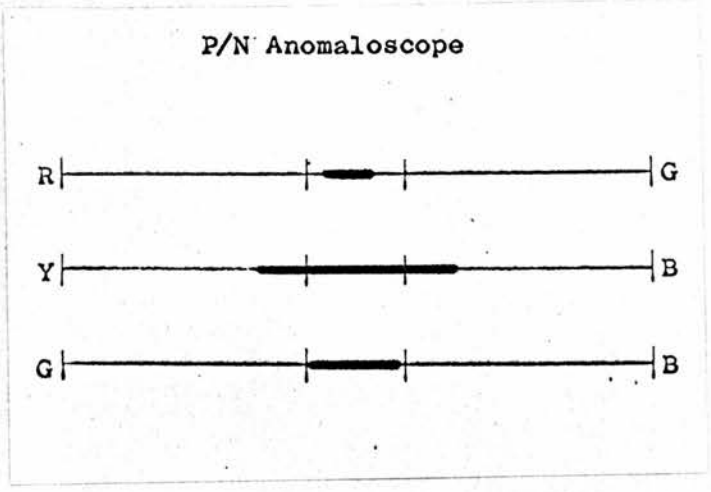
Results

Five individuals were examined on the test battery. All had a normal fundal appearance and normal visual acuity on ophthalmoscopy. They represented three generations of one family, and included three children (two male and one female), their mother, and their maternal grandfather.

The results on the children were as follows. The daughter had normal visual function on all tests, including the yellow/blue and blue/green anomaloscope equations. The cross-over time in dark adaptation was at the early point of the normal range but not significantly different from normal. The two sons had grossly abnormal visual function on dark adaptation with no cross-over point and scotopic losses of the order of 2 log units. One boy had normal colour vision and foveal differential threshold. The other boy had an abnormal static perimetric profile and abnormal colour vision, which was detectable/







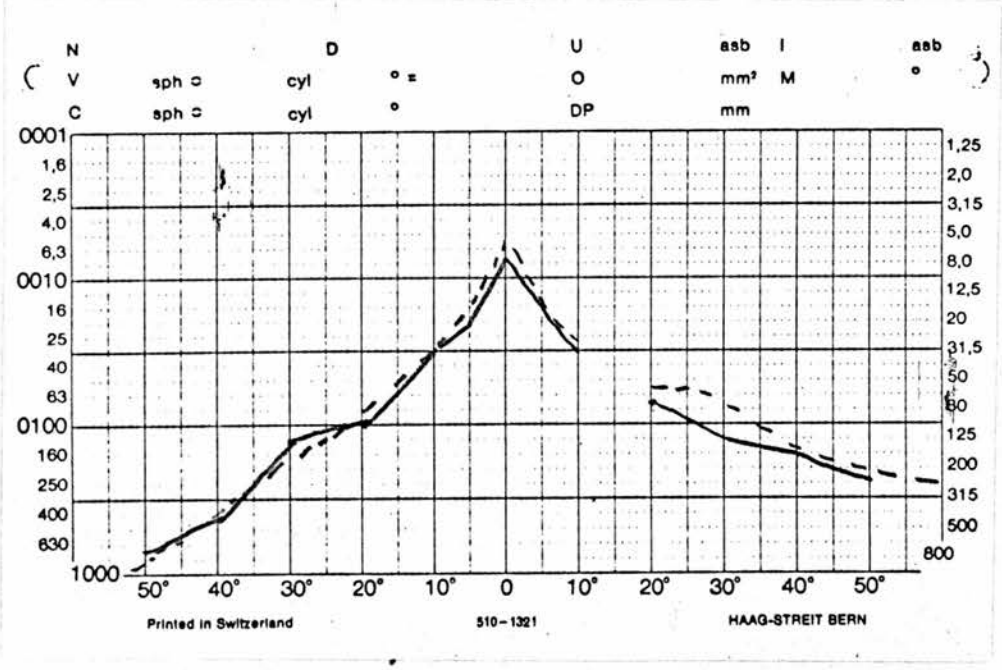
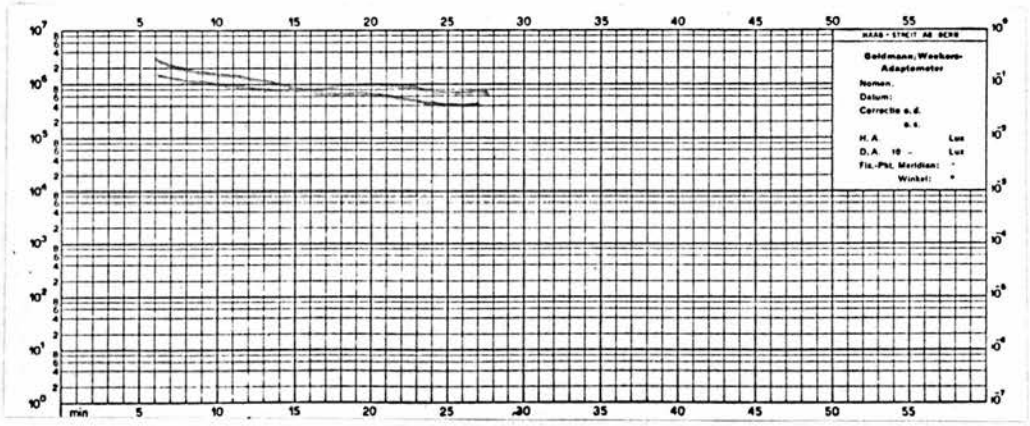
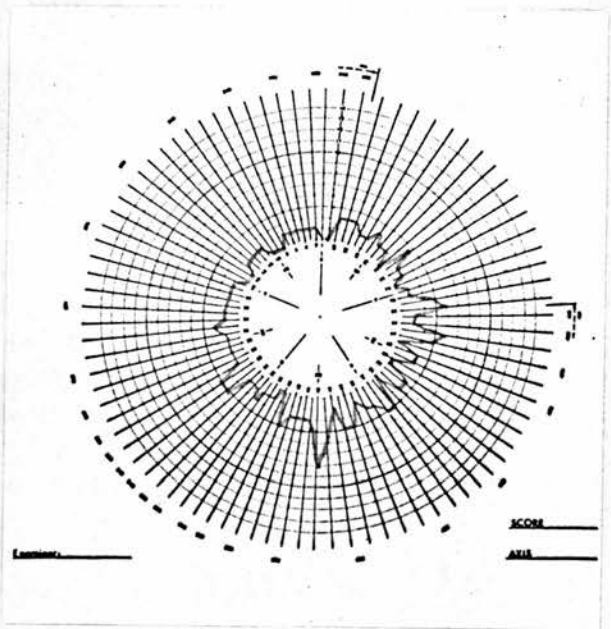
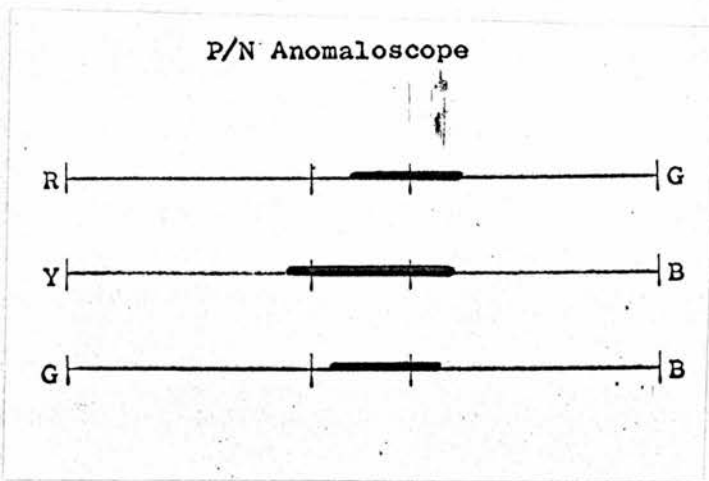


Figure 135 Congenital Nyctalopia







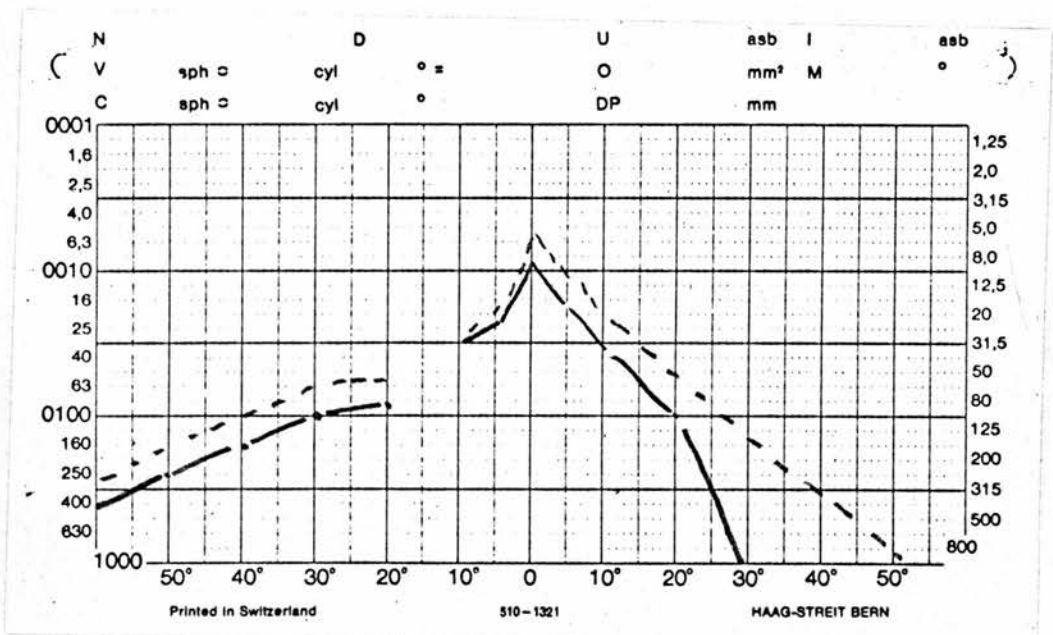


Figure 136 Congenital Nyctalopia

detectable on the 100 hue test and also present on all three anomaloscope equations, although the blue/green equation was most affected.

The results on the mother are of particular interest in this family. They are shown in Fig. 135 . The Ishihara, AOHRR and 100 hue results were all normal. The anomaloscope showed an extended loss outwith normal limits on only the yellow/blue equation. Static perimetry was normal but dark adaptation showed raised thresholds in the scotopic function. There was, therefore, firm evidence for both yellow/blue and scotopic losses in visual function.

The results on the maternal grandfather are shown in Fig. 136 . The Ishihara, AOHRR and 100 hue test were all normal. The anomaloscope showed minor losses on blue/green and yellow/blue but an extended loss on the red/green equation with a shift in mid-matching point towards the green. The static perimetric profile was normal, with the exception of points at 30°, 40° and 50° in the nasal field. The dark adaptation results were highly abnormal with scotopic losses of the order of 2 log units.

Discussion

The results show that both photopic and scotopic functions can be affected in this condition. The scotopic losses certainly dominate the visual function results and remain the clearest indication of abnormal/

abnormal vision. However fine macular tests of colour vision can reveal additional losses of varying types affecting both the yellow/blue and red/green axes of colour discrimination.

The pattern of inheritance in this family could be either a dominant or a sex linked one. The relatively small losses shown by the mother, in contrast to the extensive losses shown by her father and her two sons, would tend to support a sex linked pattern of inheritance in which the mother was a carrier.

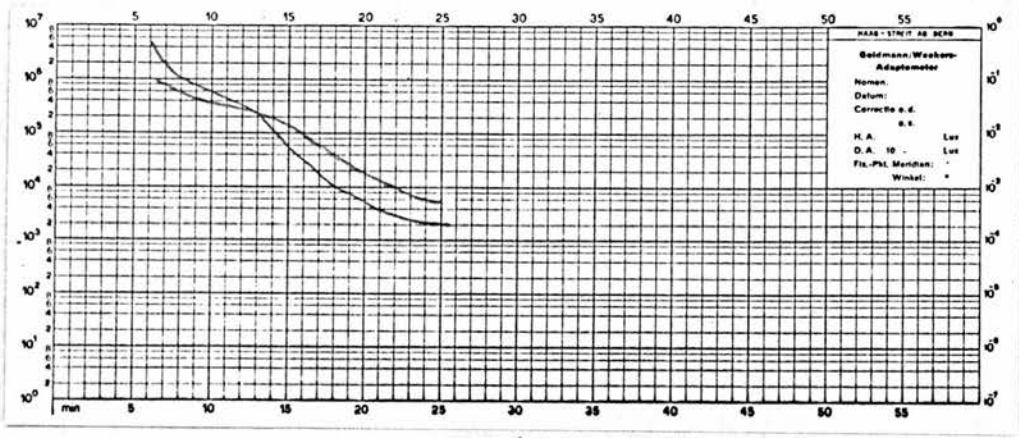
5. Myopic Degeneration

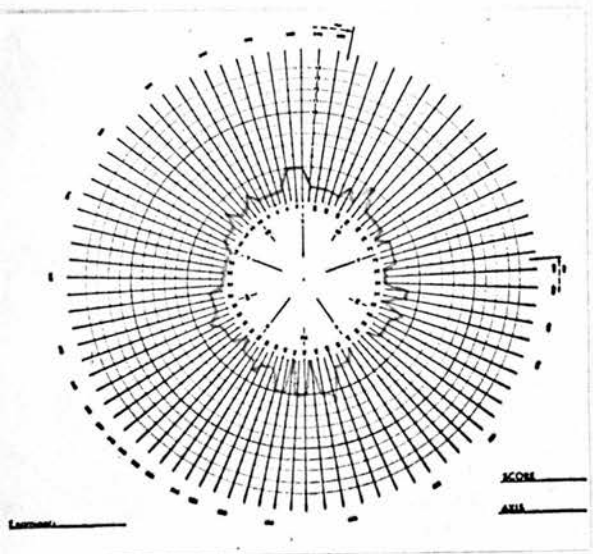
Background

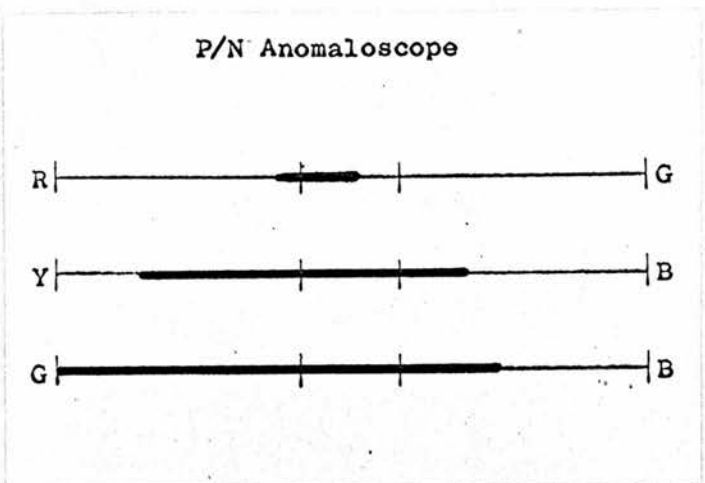
The prinicpal visual loss is reported as a reduction in sensitivity to blue light (COMBERG, 1941; ZANEN, 1953). Similarly anomaloscopic losses of the yellow/blue type are reported by FRANCOIS and VERRIEST, 1957; BOZZONI, 1959; COX, 1960, 1961; GAILLARD, 1962; VERRIEST, 1964. Less frequently, concomitant red/green dyschromatopsias have been discovered (FRANCOIS and VERRIEST, 1957; VERRIEST, 1964) which are always accompanied by a shift in mid-matching point towards the red. VERRIEST (1964) considers the colour discrimination changes to be late in this condition. (They precede visual acuity changes in a minor form but only become marked dyschromatopsias when visual acuity is affected).

Results

Six eyes were examined on the test battery. In/







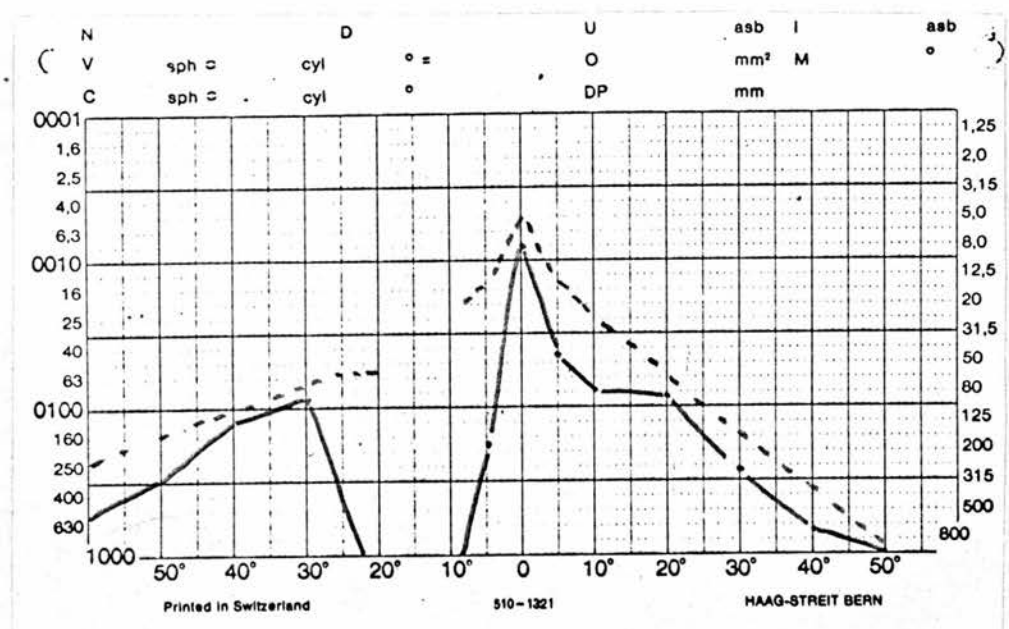


Figure 137 Myopic Degeneration

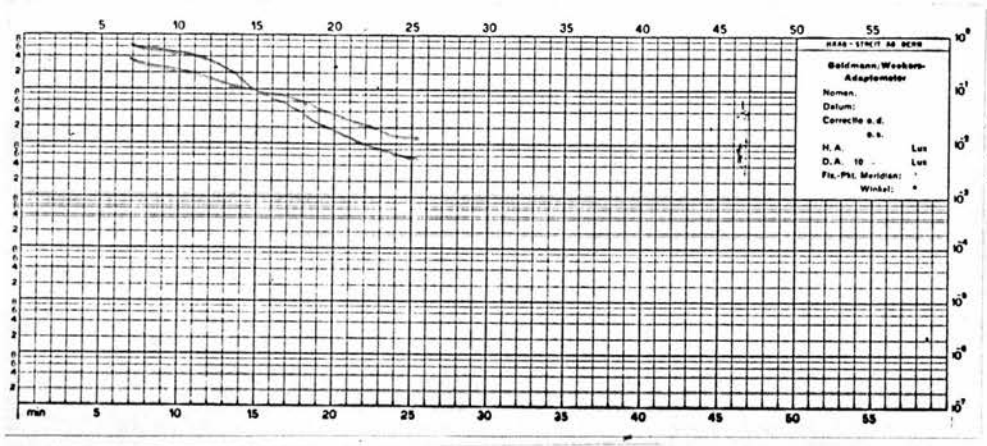
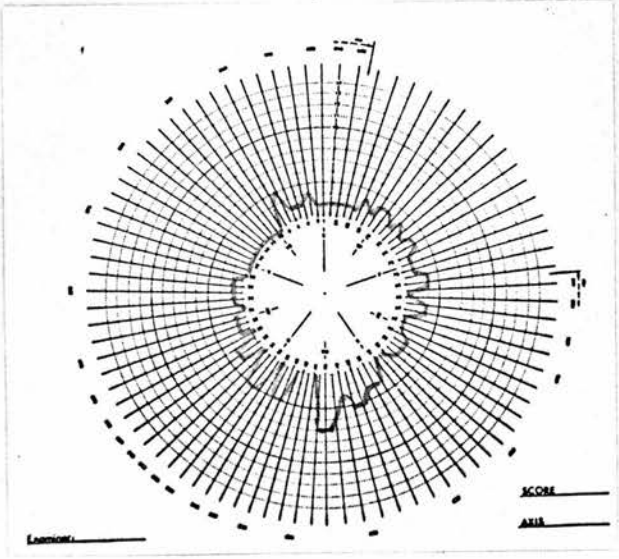
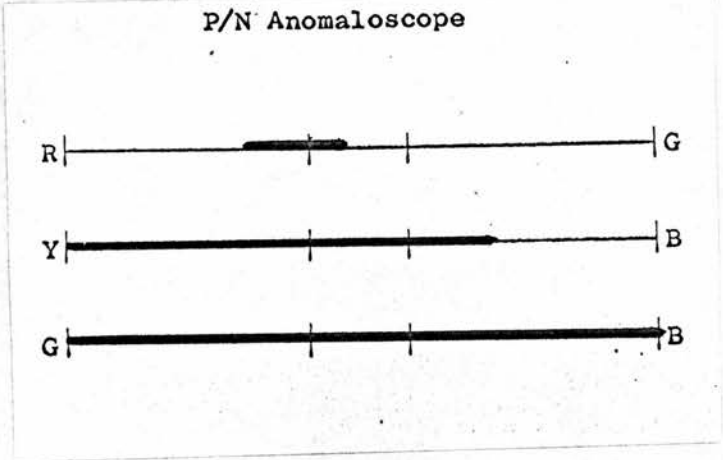


Figure 138

Myopic Degeneration





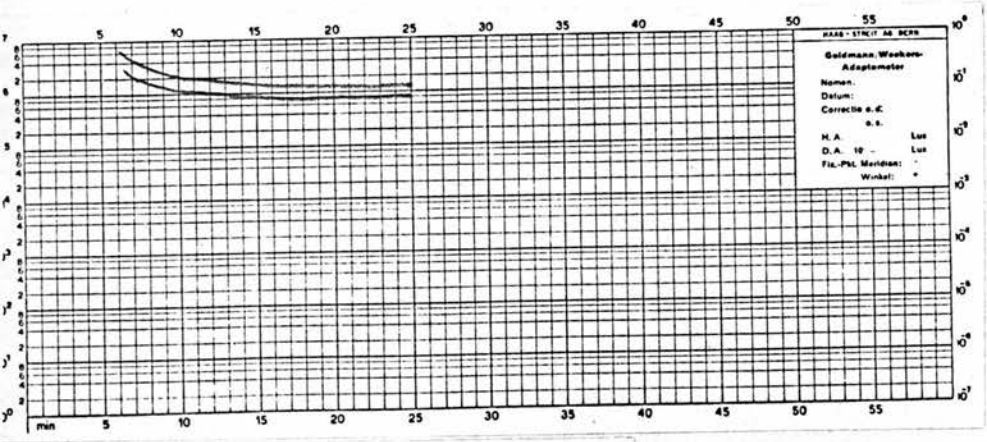
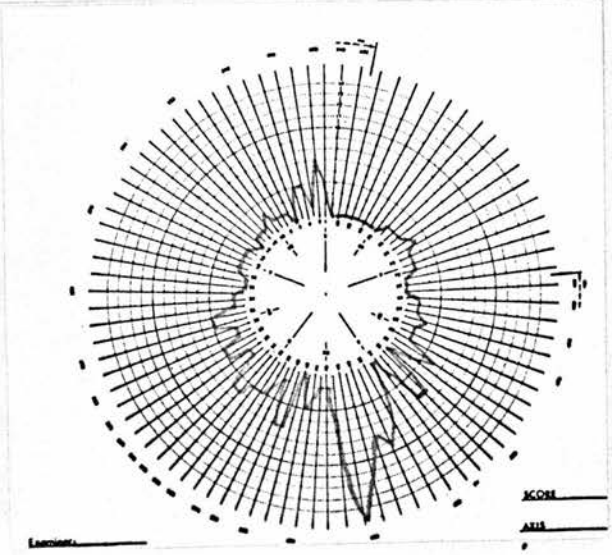
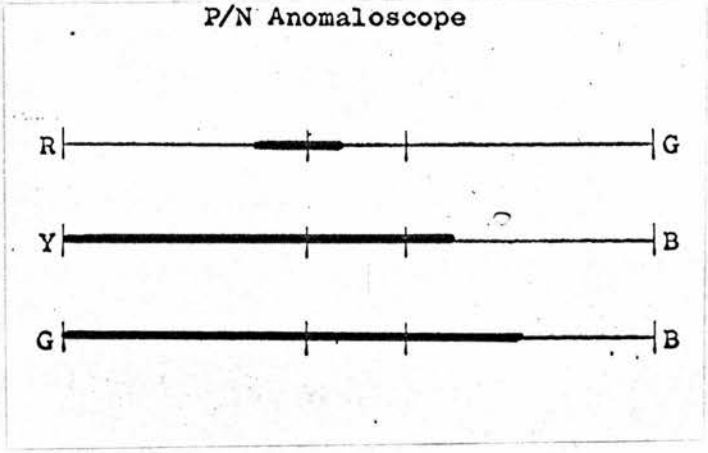


Figure 139

Myopic Degeneration





In Fig. 137 the acuity, Ishihara, AOHRR and 100 hue results are all normal. The dark adaptation curve is also normal in all respects. Abnormal function is present in static perimetry and on the anomaloscope equations. Note the extensive yellow/blue and blue/green losses and the shift (although slight) of the red/green equation towards the red. The most noticeable feature of the static perimetric profile is the loss adjacent to the optic disc at excentricities of 10^{o} and 20^{o} in the temporal field.

Fig. 138 illustrates more extensive losses although the Ishihara, AOHRR and 100 hue are again normal. Here the blue/green equation has reached the dichromatic stage and the red/green shift is more pronounced towards the red end of the spectrum. Note also the slow rate of dark adaptation with generalised rod and cone losses and the late cross-over time.

In Fig. 139 the Ishihara and AOHRR are normal but the 100 hue test is already affected with a total score beyond the normal limits and an axis centred on cap 49. The anomaloscope shows extensive yellow/blue and blue/green losses and a red/green shift. Although in this patient the anomaloscope losses on blue/green are less than in the previous case, the dark adaptational loss is greater with no evidence of scotopic function.

Discussion

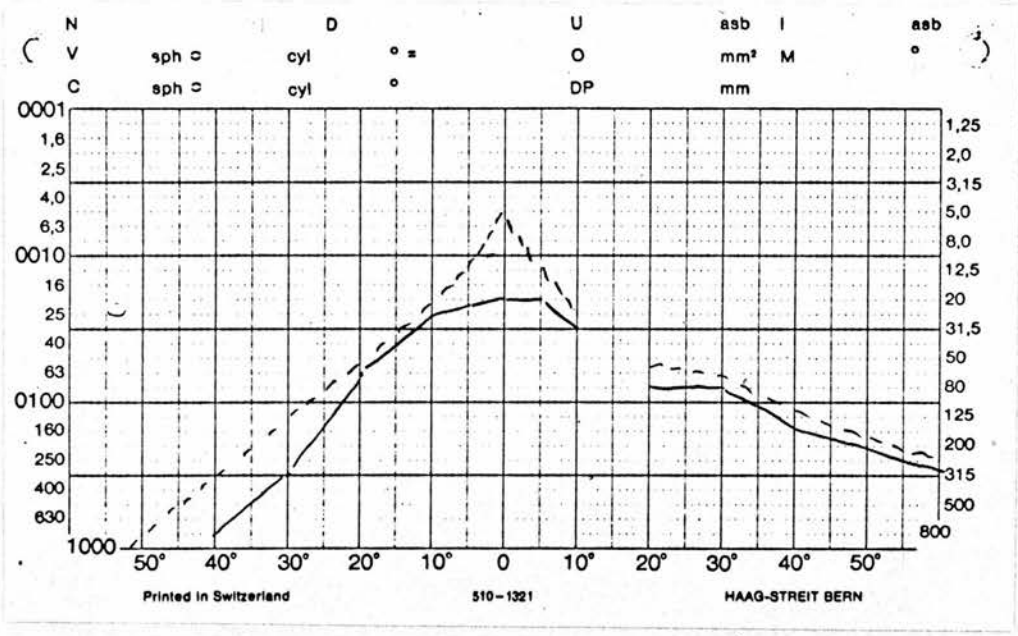
The colour vision results are in keeping with/

with previous findings with extensions in the blue/green and yellow/blue matching ranges, and shifts in the red/green mid-matching point. Fig.138 is interesting because it illustrates that the 100 hue profile may be normal in all respects although one anomaloscope equation has reached the dichromatic stage. Conversely a 100 hue axis is present in Fig. 139 although the anomaloscope equations have not reached the dichromatic stage. Additional losses can be found in this condition in both static perimetry and dark adaptation which affect the peripheral retina and the scotopic thresholds.

6. Stargardt's Syndrome

Background

Colour vision results vary from being normal SORSBY and WREN,(1960); to yellow/blue dyschromatopsias HONG, (1957); BOZZONI, (1959); COX, (1960, 1961); VERRIEST, (1964), to type I red/green dyschromatopsias FRANCESCHETTI and KLEIN, (1941); HONG, (1957); COX (1960, 1961), GRUETZNER, (1961); VERRIEST, (1964); FRANCOIS and VERRIEST (1956). A progression of the defect from the red/green axis to total achromatopsia has been proposed (FRANCOIS and VERRIEST, 1956). Similarly GRUETZNER (1961) proposed a sequence from normal colour matches via protanomalous and protanopia to total achromatopsia. The most comprehensive study, by VERRIEST (1964), showed that the condition gave rise to the type I red/green dyschromatopsia but that the/



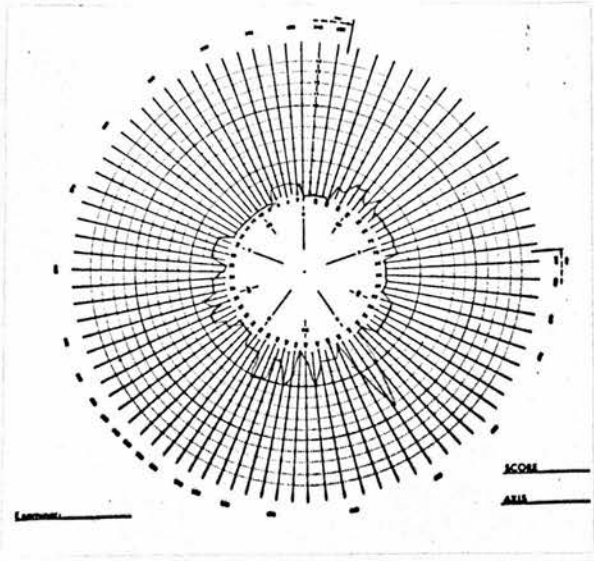


Figure 140 Stargardt's Syndrome

the yellow/blue axis was also affected so that the axis of the defect was difficult to determine. The shifts in mid-matching point towards the red were early signs before visual acuity was affected. Static perimetry showed central scotomas (particularly to red targets) with normal peripheral thresholds. Recently DEUTMAN (1972) has confirmed the red/green defect with the loss in sensitivity to red followed by the progression to achromatopsia as above. The loss in red sensitivity is seen as the most characteristic visual loss in early stages of this condition.

Results

Three eyes were examined by means of the Ishihara plates, the 100 hue test and static perimetry. The visual acuity and Ishihara results were normal in the three cases. Similarly the 100 hue results were well within the normal range in two subjects with no indication of axial defects. Static perimetry was normal in two of the cases but showed evidence of central suppression to the white target in the other patient. Fig.140 shows the 100 hue and static perimetric profile for this patient. Whether or not the 100 hue profile is considered to have a red/green axis is debatable. It is the writer's view that this does not consitute a red/green defect and furthermore that acquired red/green defects are only rarely discernable on this test (see below)./

below).

The only conclusion to be drawn from these results is that in a limited test situation, colour vision can be normal in this condition and that static perimetry can show a central loss to a white target while the total 100 hue error score is still within the normal range.

7. Retrobulbar Neuritis

Background

Typical scotomas for red and green targets have been reported in this condition WILBRAND and SAENGER (1913). Thus a red/green axis has been recognised by KOENIG (1897), SLOAN (1942), HONG (1957), OHTA (1961), COX (1960, 1961), GRUETZNER (1961), VERRIEST (1964). SLOAN (1942) showed that the reading of pseudo isochromatic plates was often abnormal although visual acuity was good. The red/green anomaloscope equation was widened or shifted towards the green. Another study using the Ishihara (LYNN, 1959) in 127 subjects with a unilateral neuritis, demonstrated that in 23 cases both eyes were normal, in 43 cases the single eye was affected, and in 61 cases both eyes were affected. COX (1960, 1961) found in six subjects that one had normal colour discrimination, and the other 5 had red/green dyschromatopsias. A follow-up of the development of the condition showed that during healing the defect resembled firstly congenital deuteranopia, and then/

then congenital deuteranomaly. The 100 hue test (and in particular the error on cap 18) was seen to be useful in following the progress of the condition.

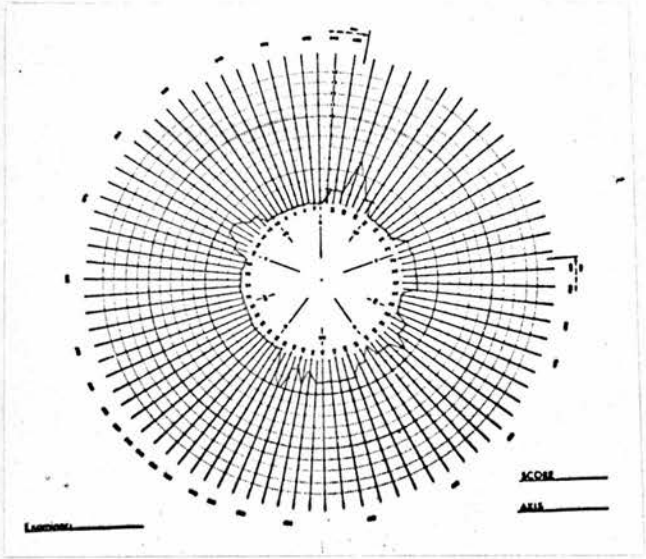
Although most reports focus on red/green defects, BOZZONI (1959) found either anarchic or tritan type outlines on the 100 hue test. Finally VERRIEST, (1964) found predominantly a type II red/green dyschromatopsia. Only when the condition was progressing to achromatopsia was a concomitant yellow/blue defect present. Contrary to above reports, Verriest found no shift in the red/green equation but only a general widening of the matching range.

Results

Seven eyes with unilateral retrobulbar neuritis were examined on the AOHRR, Ishihara, 100 hue test and the Pickford Nicholson anomaloscope. In addition the foveal differential threshold and final scotopic thresholds were measured. The fellow eyes were also tested. A minimum of 6 months had elapsed since the onset of the condition.

The results of the affected eyes were as follows:-

1. The AOHRR test was normal in 4 eyes and abnormal in 3.
2. The Ishihara test was normal in 2 eyes and abnormal in 5, (abnormal results ranged from 5 mistakes to 20 mistakes).
3. The 100 hue test was normal in 4 eyes and/



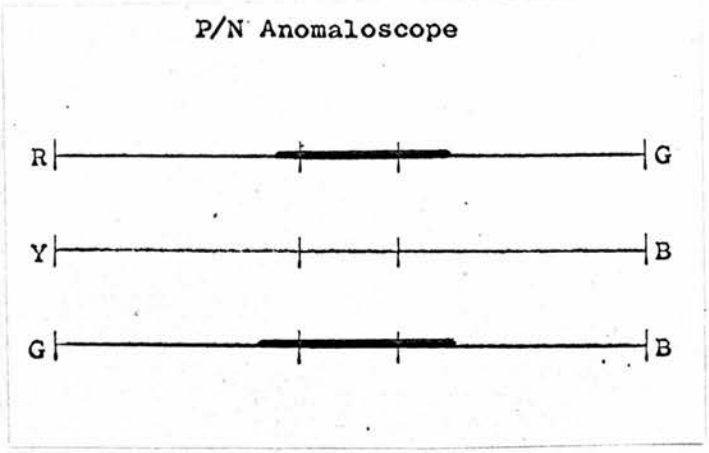
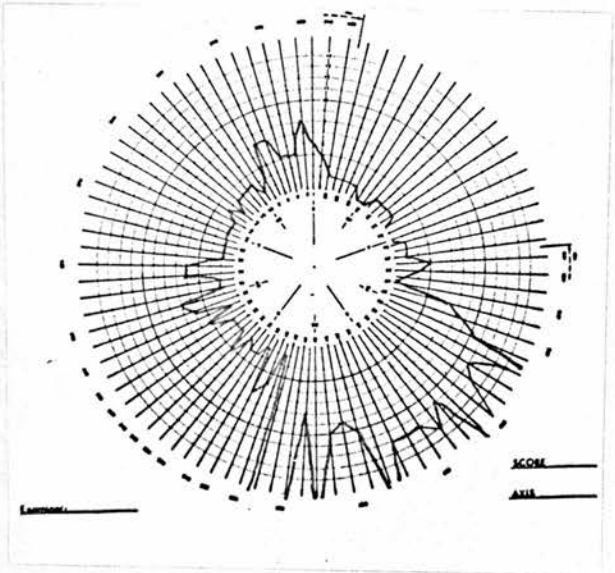


Figure 141 Retrobulbar Neuritis



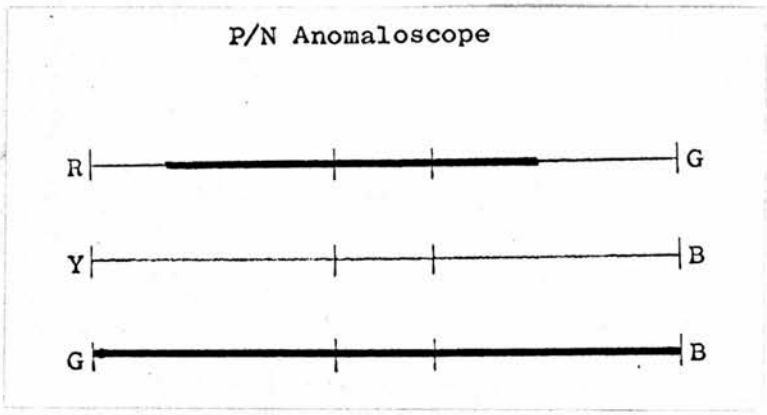


Figure 142 Retrobulbar Neuritis

and abnormal in 3. Two of the abnormal profiles were anarchic, and the third had a monopolar bulge extending from the tritan to the deuteranopic axis (see Fig. 142).

4. The anomaloscope red/green equation was normal in 1 eye and abnormal in 6. The mid-matching point was stable about the normal position, showing no tendency to shift towards the green. The blue/green equation was also normal in one eye and abnormal in 6. Three of the abnormal matching ranges were at the dichromatic stage.
5. Foveal differential threshold results were normal in 4 eyes and abnormal in 3.
6. Dark adaptation thresholds were normal in 5 eyes and abnormal in 2. The abnormal thresholds were slightly raised (0.5 log units) in 2 eyes with the most extensive red/green losses and dichromatic blue/green matching ranges.

Of the 7 patients, only one had normal visual function on all the tests in the battery. The results on the fellow eyes were normal in 5 patients but abnormal in 2. The red/green and blue/green anomaloscope equations were normal in the same 5 cases and abnormal in the same 2 cases.

Two individual cases indicate the range of abnormal function in the group. In Fig. 141, the 100 hue test is normal, dark adaptation and foveal differential/

differential threshold are normal, 5 mistakes are made on the Ishihara, and the red/green and blue/green matching ranges are both beyond normal limits but comparable in extent.

In Fig. 142 all the tests show losses. The blue/green equation is at the dichromatic stage and there are extensive red/green losses. The 100 hue profile has a monopolar bulge (including both the tritanopic and deuteranopic axes) centred on cap 53. This would probably be interpreted as a red/green axis, although the anomaloscope shows that it is the blue/green axis that has truly reached the dichromatic stage.

Discussion

Colour vision appears to be affected at an early stage of this condition and the photopic and scotopic luminance thresholds only appear to be affected when colour vision losses are extensive. The Ishihara test appears to be more sensitive to abnormalities of function than either the AOHRR plates or the 100 hue test. The Pickford Nicholson anomaloscope remains the most sensitive test in the battery. Although most authors stress the characteristic red/green anomaly, it is clear from the anomaloscope equations that if the test is sufficiently sensitive, blue/green anomalies are detectable. In this group the blue/green and red/green losses correlate closely with each other so that it is/

is difficult to determine whether one defect is more extensive than the other. Consequently the results are contrary to previous findings in that the blue/green loss is detectable when the red/green loss is relatively small. Similarly in eyes where the visual losses are extensive, the blue/green equation reaches the dichromatic stage before the red/green losses reach this level.

In agreement with the results of VERRIEST (1964), the extension of the red/green matching range is symmetrical about the mid-matching point and there was no tendency for a shift in the mid-matching point towards deuteranomaly.

8. Ischaemic Optic Neuropathy

Background

The condition is associated with defects of the yellow/blue axis (ADROGUE and MALBRAN, 1933) and defects of the red/green axis (HACK, 1933; COX, 1960, 1961; VERRIEST, 1964). Of the recent studies both COX and VERRIEST found a type II red/green defect resembling congenital deuteranopia.

Results

Two patients were examined on the test battery. The dark adaptation, foveal differential threshold results, visual acuity results and 100 hue results were normal. The Ishihara results and anomaloscopic results were abnormal. All 3 anomaloscope equations were/

were abnormal with comparable matching ranges. In contrast to the results of previous authors a distinct shift in mid-matching point towards the red was found.

9. Central Serous Retinopathy

Background

A red/green dyschromatopsia, with shifts in mid-matching point towards the red is described by MORI (1916); OBI (1952); HONG (1957); FRANCOIS and VERRIEST (1957); VERRIEST (1964). Red/green losses are also described by DUBOIS-POULSEN (1948, 1952) but the red/green equation, if abnormal, is shifted towards the red in some cases and towards the green in others. OBI (1952) describes a widening of the red/green matching range which precedes a shift towards the red.

On the other hand there are several reports of yellow/blue dyschromatopsias in this condition (JAEGER and NOVER, 1951; ZANEN, 1959; COX, 1960, 1961; VERRIEST, 1964). The order of colour vision losses is therefore important. JAEGER and NOVER (1951) describe firstly a blue/green dyschromatopsia, followed by the shift on the red/green equation towards the red. However, COX (1960, 1961) found one patient with reduced visual acuity (to 0.3) but normal colour discrimination. A second patient had a red/green defect, and a third had predominantly a yellow/blue defect. VERRIEST (1964) finds the yellow/blue dyschromatopsia to be most prevalent. Dyschromatopsias without axis were also found. However/

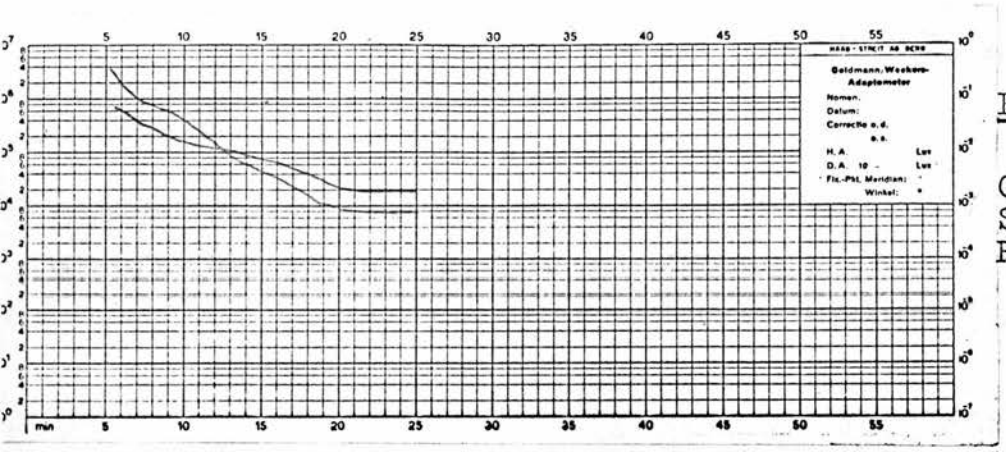
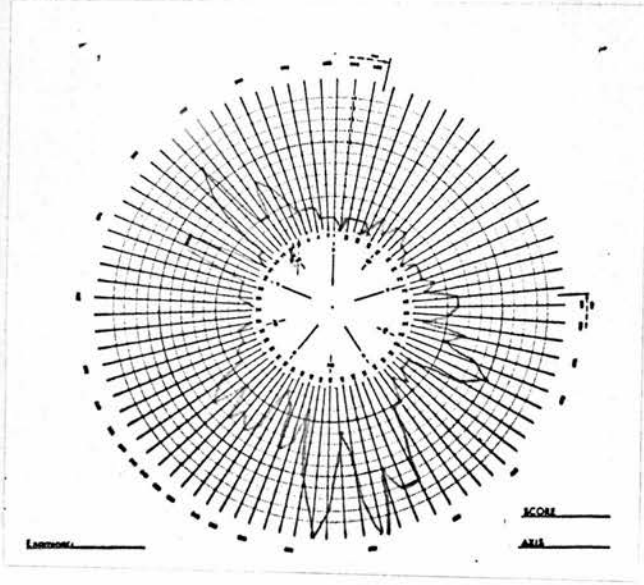
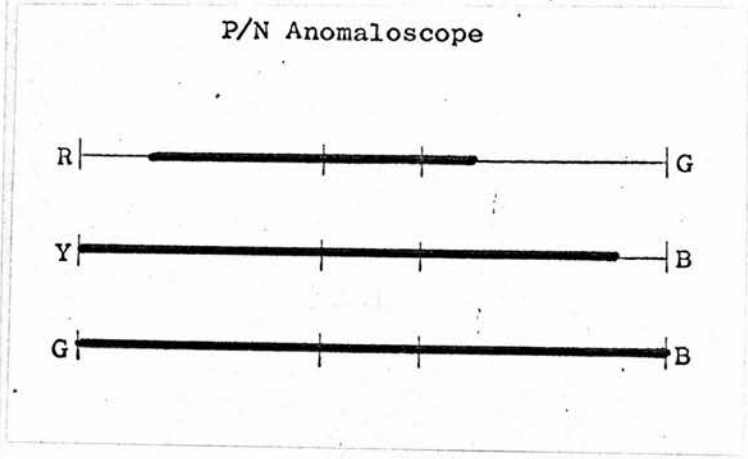


Figure 143

Central Serous Retinopathy - after 2 weeks





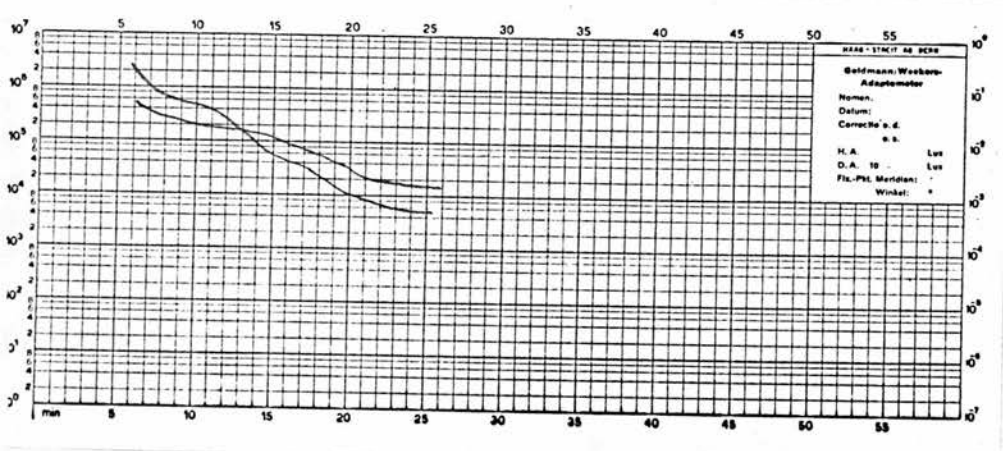
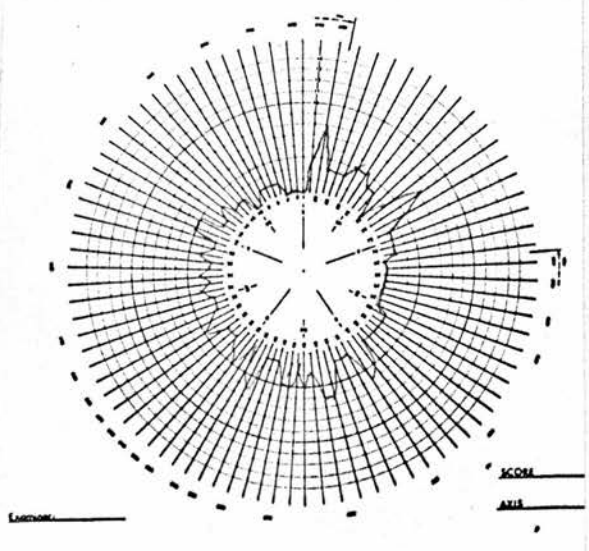
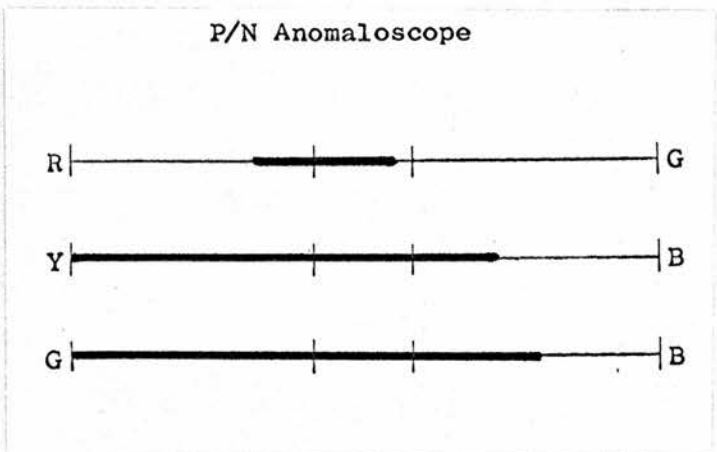


Figure 144

Central Serous Retinopathy - after 2 months





However, the red/green losses were minor, and the yellow/blue axis of the defect was easy to detect. The red/green defects were always of the form of a shift towards the red end of the spectrum. Contrary to the findings of Cox, Verriest never found normal colour discrimination when acuity was reduced beyond 0.8. Colour vision changes therefore were again seen as early symptoms of the disease.

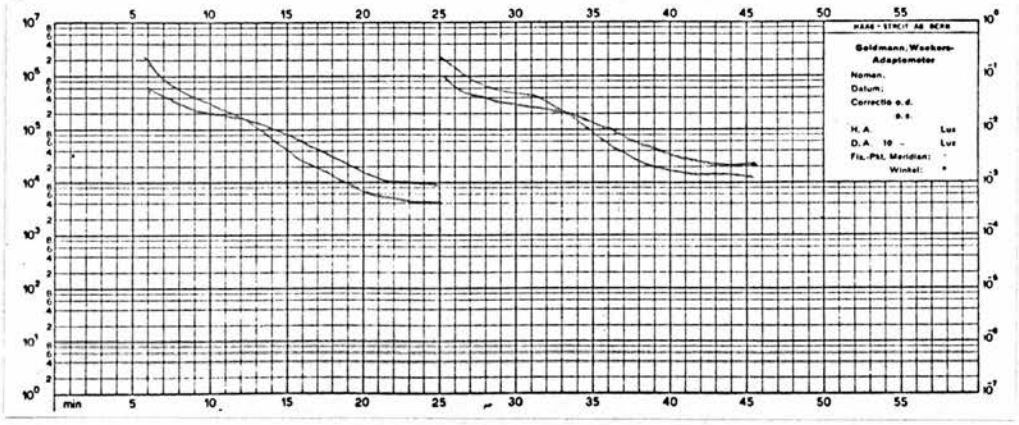
Results

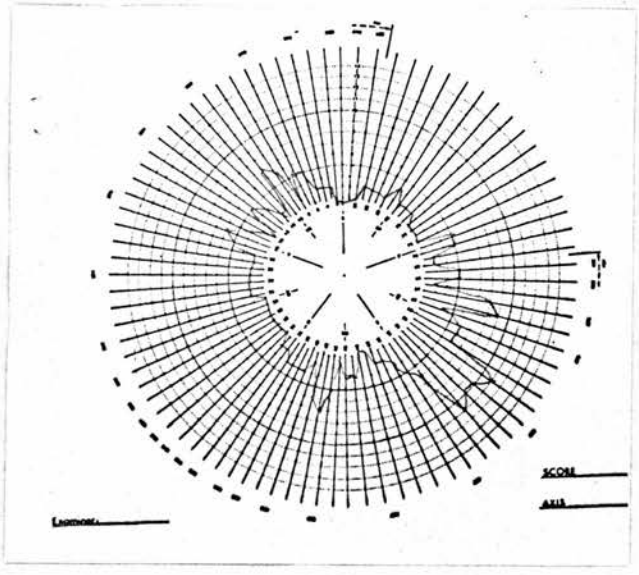
Twelve eyes were examined on the Ishihara, 100 hue test, Anomaloscope equations, foveal differential threshold, and dark adaptation. Eight eyes had central serous retinopathy; the four fellow eyes were tested.

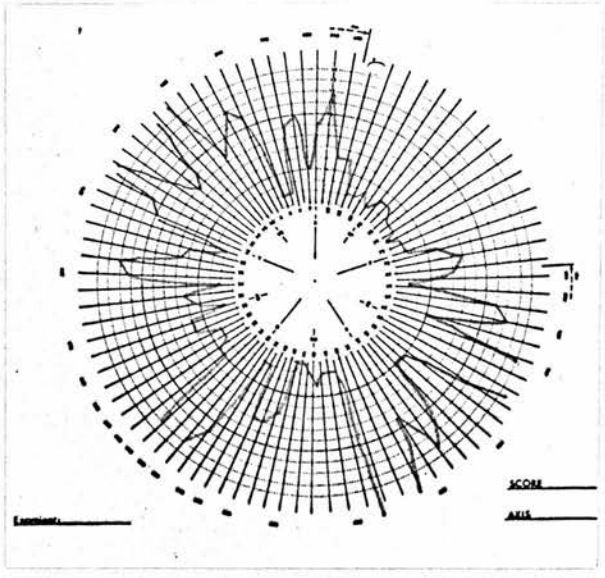
The first patient was tested two weeks after the onset of the disease, and then two months later. The results at two weeks are shown in Fig. 143. Snellen visual acuity was 6/12 and 2 mistakes were made on the Ishihara plates. Note the axial nature of the 100 hue test. The anomaloscope showed that the red/green equation was shifted into the red with extensive losses in discrimination. The blue/green equation was dichromatic and the yellow/blue equation was almost at the dichromatic stage. (The red/green discrimination of the fellow eye was also extended just beyond the 95th percentile of the normal population). The dark adaptation curve showed slightly raised thresholds, and the foveal differential threshold was raised 0.5 log/

log units beyond the normal limit. When tested 2 months later, the visual acuity and foveal differential threshold were normal. The results are shown in Fig. 144. Note firstly that the dark adaptation curve is almost identical to that at the first time of testing. The 100 hue profile has improved considerably and the former axis has disappeared. The anomaloscope shows the improvement on all three equations. However the red/green axis is still abnormal and the red shift is still present. The blue/green equation is no longer dichromatic but extensive losses are still present.

The next three patients were tested one month after onset. In the first patient visual acuity was 6/9. The foveal differential threshold and dark adaptation showed losses (0.5 log units). One mistake was made on the Ishihara and the 100 hue profile was normal. The anomaloscope showed extensive red/green losses but no shift in the mid-matching point. The blue/green equation was dichromatic. The second patient had similar acuity and foveal differential thresholds. The 100 hue profile was anarchic and abnormal (error score 283). The anomaloscope showed dichromatic matching on blue/green, extensive red/green losses and a pronounced red/green shift. The third patient in the group had an acquired defect superimposed on a congenital dyschromatopsia. A comparison of the affected and unaffected eyes is/







P/N Anomaloscope

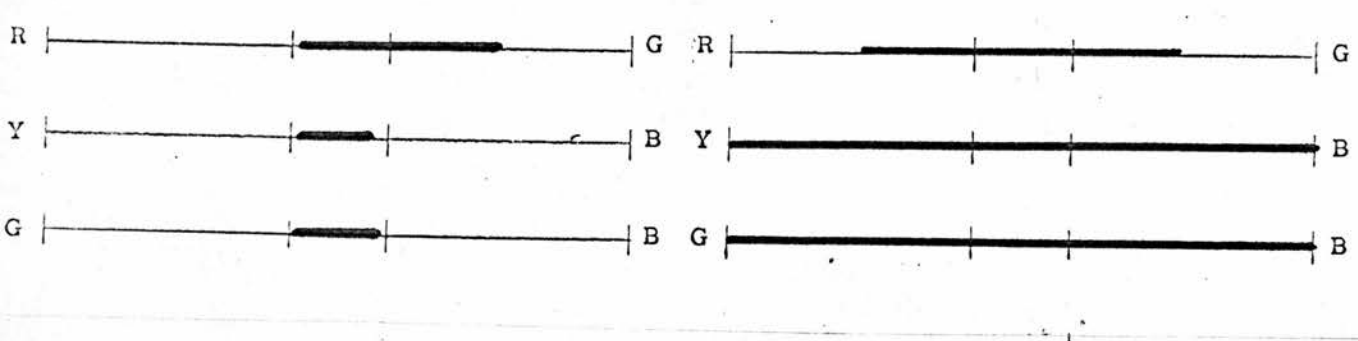


Figure 145 Central Serous Retinopathy
A comparison of the affected eye and unaffected eye in a case of hereditary extreme deuteranomaly

is shown in Fig. 145. Visual acuity in the affected eye was 6/9 and in the unaffected 6/5 . The dark adaptation results indicate a slight loss in the thresholds of the affected eye. The 100 hue results show the monopolar bulge in the normal eye and the extensive losses superimposed on this in the abnormal eye. The anomaloscope confirms the hereditary defect as extreme deuteranomaly in the normal eye and shows the yellow/blue and blue/green equations to be within normal limits but at the 90th percentile of the normal population. In the affected eye the extensive red/green losses are symmetrically placed about the mid-matching point and the other two equations are at the dichromatic stage.

Finally two patients were tested after an interval of one year from the onset of the disease. In both patients the visual acuity, foveal differential threshold, 100 hue test and the dark adaptation were normal. In one patient, all three anomaloscope equations were normal, but the colour discrimination was bordering on the 95th percentile in each equation. In the second patient the anomaloscope result was just beyond the 95th percentile on the red/green equation, with a shift towards the red, and just within the 95th percentile on the yellow/blue and blue/green equations.

Discussion

The results indicate the presence of red/green and/

and yellow/blue losses in this condition. The red/green and yellow/blue losses appear to change together so that when the dichromatic stage of a yellow/blue or blue/green loss is apparent, there are already extensive red/green losses. Similarly, where the colour vision has returned within normal limits, the red/green, yellow/blue and blue/green matching ranges all border on the 95th percentile. When very minor anomaloscope losses exist on the red/green equation, the yellow/blue and blue/green equations are both within but bordering on the normal limits. It appears therefore that there is a close parallel between the yellow/blue and red/green dyschromatopsias. Contrary to Verriest's finding, there is no indication of a yellow/blue loss preceding a red/green loss, and contrary to OBI (1952) there is no evidence for an enlarged red/green matching range preceding a shift towards the red end of the spectrum. This shift appears to be a characteristic feature which occurs as soon as any other losses occur. (Only one case of extensive losses was found where the matching range was symmetrical about the mid-matching point). An unusual confirmation of this shift is apparent in the individual with an acquired defect superimposed upon a hereditary defect. The individual has an extreme deuteranomaly in which the mid-matching point is originally shifted well into the green. The loss in the affected/

affected eye is subsequently summetrical about the normal mid-matching point. Consequently a relatively greater movement towards the red than movement towards the green must have occurred in the affected eye. The 100 hue test can be normal when marked colour vision losses are present. However it can provide a useful means of following recovery after extensive visual losses. The dark adaptation results show relatively minor losses in this condition, even when colour vision is markedly affected.

10. Choroiditis

Background

General agreement exists concerning a yellow/blue dyschromatopsia, especially at the early stages of development of this condition. (FRANCOIS and VERRIEST, 1957; ZANEN, 1959; BOZZONI, 1959; COX, 1960, 1961). Additional losses of the red/green axis have been observed by HONG (1957) and VERRIEST (1964), who found a pronounced concomitant red/green defect at a later stage of the defect. Colour vision was abnormal while visual acuity was still normal.

Results

Two eyes were examined on the test battery. The visual acuity and 100 hue scores were normal in both cases. Both eyes showed enlarged yellow/blue and blue/green matching ranges with normal red/green discrimination. Dark adaptation results were abnormal with generalised/

generalised photopic and scotopic losses. Static perimetry in one patient showed marked peripheral construction in both nasal and temporal fields. The results confirm the yellow/blue dyschromatopsia in this condition and show that additional peripheral and adaptational losses are present.

11. Retinopathy with Angioid Streaks

Background

ZANEN (1959) found normal visual acuity and colour discrimination in this condition but raised photochromatic intervals to long wavelengths. Verriest also noted normal colour discrimination in one case, and a small yellow/blue dyschromatopsia in another case.

Results

Three eyes were examined on the Ishihara, 100 hue test, dark adaptation and static perimetry. In two eyes the visual function results were normal on all tests. In the third eye, visual acuity was reduced to 6/9 and 4 mistakes were present on the Ishihara. The 100 hue test was within the normal limits but bordering on the 95th percentile score with a suggestion of a tritan axis. The dark adaptation results were abnormal with generalised photopic and scotopic losses (0.5 log units) and a late cross over time. The static perimetric profile was irregular with generalised losses across a horizontal meridian.

12. Atypical Pigmentary Degeneration of the Retina/

12. Atypical Pigmentary Degeneration of the Retina

Twenty two eyes were examined on the test battery. As the group contains different types of pigmentary degeneration, the interrelation between the tests is the major concern.

Results

The first patients in the group were a girl and her grandmother with central and peripheral pigmentary degeneration. The results of the girl showed extensive colour vision and dark adaptational losses. No Ishihara plates were read and the 100 hue profile was grossly abnormal. The anomaloscope showed extended matching ranges on the red/green and blue/green equations of equal amounts. The results of the grandmother showed anarchic colour vision (100 hue error score of 204) and dark adaptational losses with a reduced rate of adaptation and a late cross over time. A further patient with more extensive degeneration had a similar anarchic 100 hue score (of 482) and no scotopic function on dark adaptation.

Four eyes in the sample had pigmentary degeneration and colloid bodies. No scotopic function was present in any case, and the blue threshold was above the yellow after 20 minutes into dark adaptation. The colour vision results on the 100 hue test were all around the 200 error score range. Three eyes had anarchic profiles and one eye had a tritan profile. The/

The anomaloscope results on two eyes indicated yellow/blue and blue/green losses and normal red/green function. On the other two eyes the yellow/blue and blue/green losses were greater and a red/green loss had appeared. Static perimetric profiles were irregular and abnormal with mainly peripheral suppressions. One case with peripheral pigmentary and disciform degeneration had no scotopic function in dark adaptation but relatively good colour discrimination with a 100 hue error score of 142. Two further cases with pigmentary and disciform macular degeneration had grossly abnormal anarchic colour vision but only moderate dark adaptation losses with a late cross over point and raised scotopic thresholds. In the first instance the loss in the central region was mainly scotopic, but in the second case it was predominantly photopic.

A case of choroidal sclerosis and primary pigmentary retinal degeneration showed gross anarchic colour vision losses (the 100 hue score was 675) and gross dark adaptation losses. Although the yellow/blue loss was dichromatic the red/green loss was relatively minor extending to the deuteranomalous and protanomalous points.

The next two cases of interest consist of a male with congenital syphilitic pigmentary degeneration of the retina and his sister. The male had gross adaptation losses. Colour vision was abnormal by similar amounts/

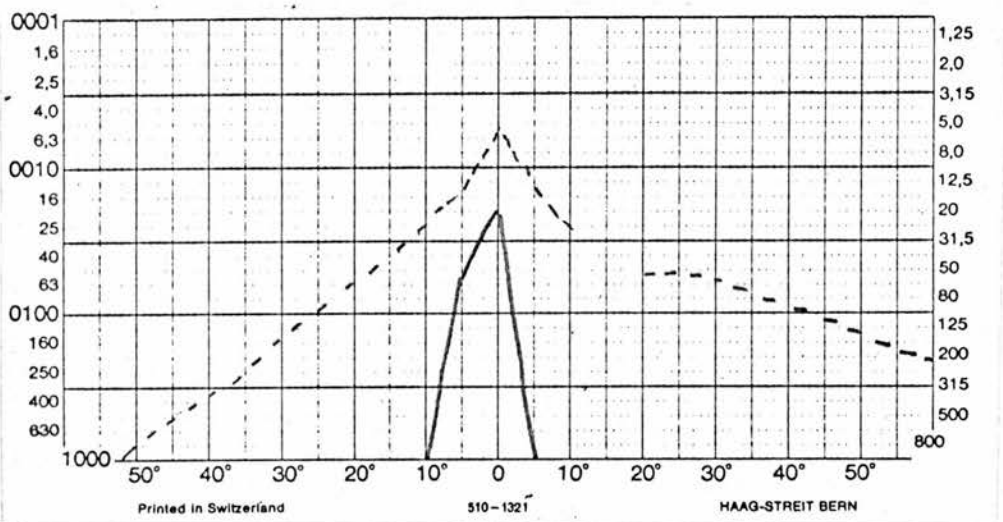
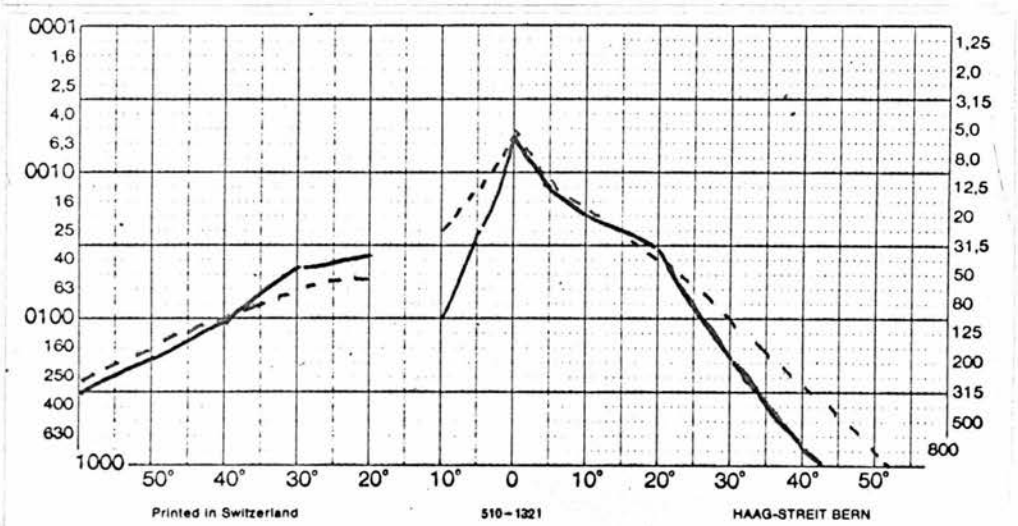
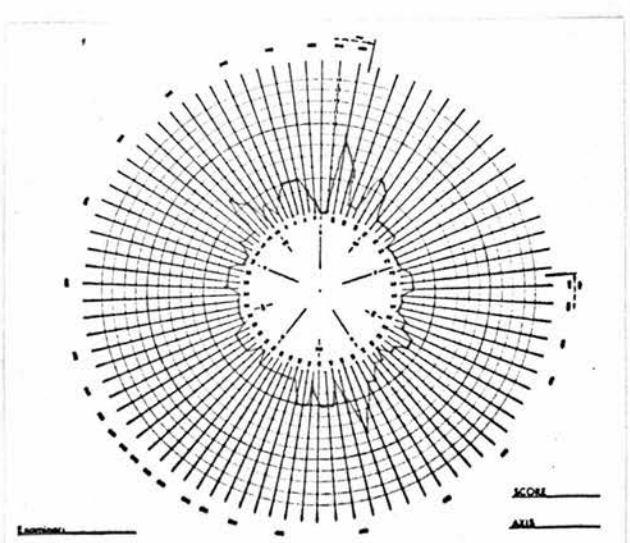
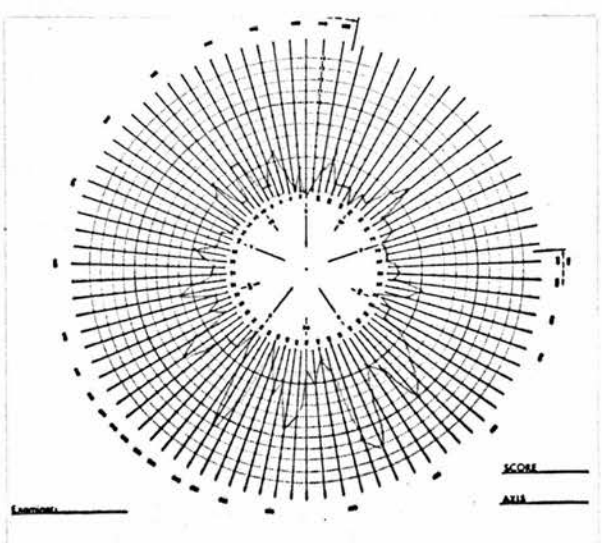


Figure 146

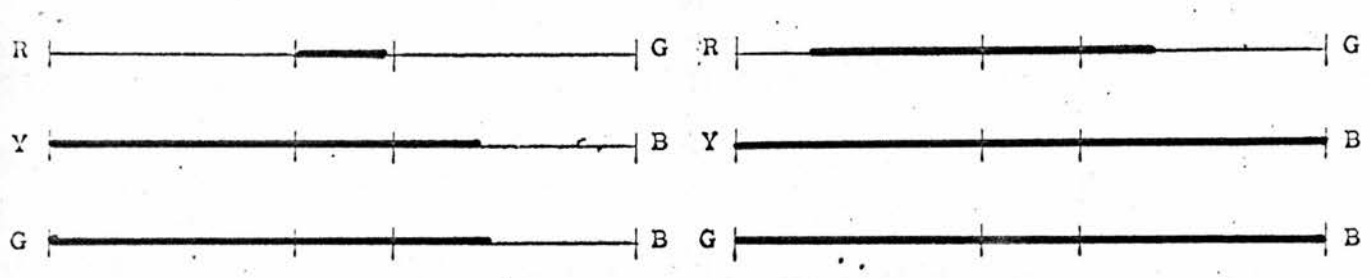
Tapeto
Retinal
Degeneration







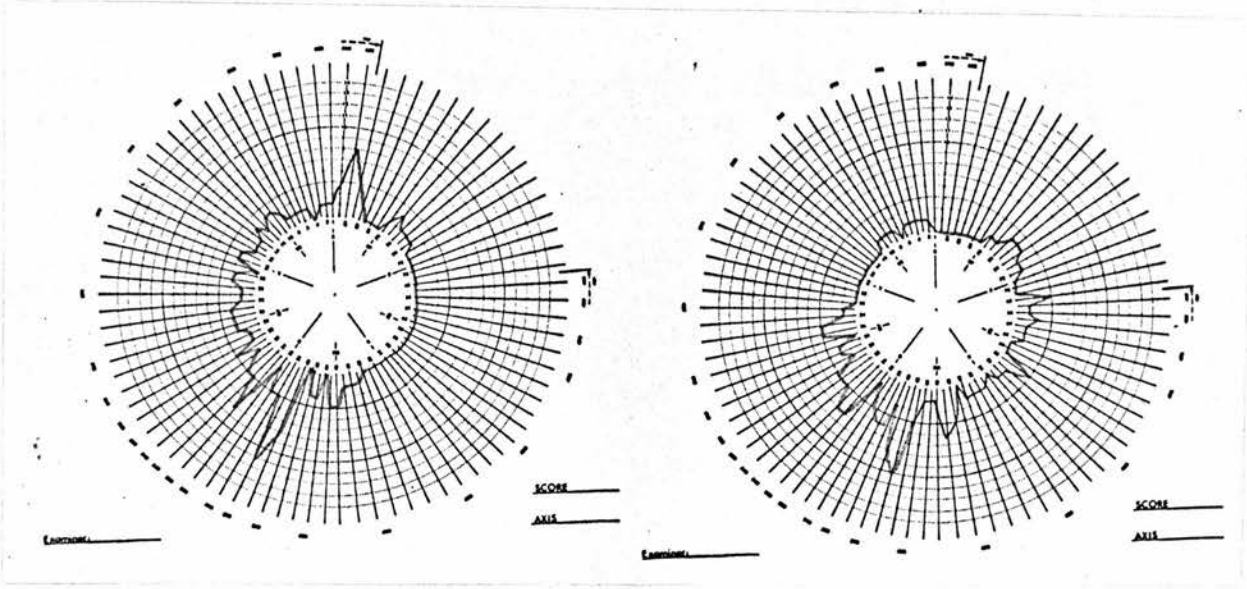
P/N Anomaloscope



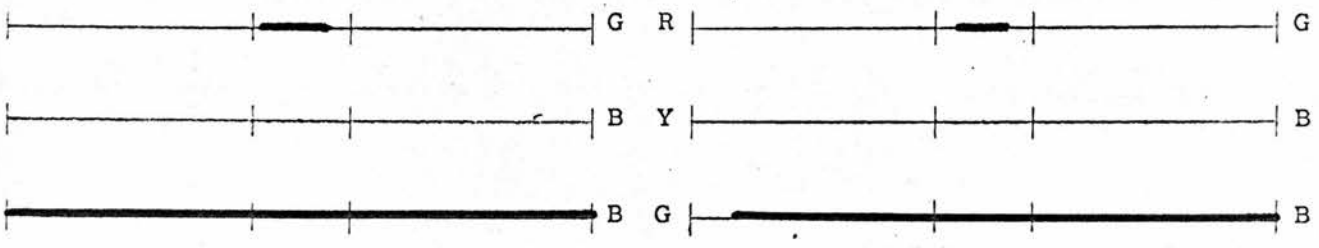
amounts on all three equations. The 100 hue score was just abnormal. The results of the sister are particularly interesting, as she was clinically almost normal with only slight depigmentation. The 100 hue score was well within the normal range. However the anomaloscope results were identical with those of her brother. On dark adaptation there were moderate losses (1.0 log units) in cone and rod function and an extremely late cross over.

Finally an interesting case of tapeto retinal degeneration is shown in Fig. 146 . The right eye was affected but the left eye was clinically normal, and had a normal E.O.G. and E.R.G. The most obvious difference between the eyes was shown on static perimetry. Note however the losses in the left eye adjacent to the optic disc and in the nasal field. The 100 hue score shows an example of a tritanopic profile within the normal total error score for the left eye. The right eye profile is anarchic. The left eye anomaloscope scores are already abnormal on the yellow/blue and blue/green equation. The right eye has reached the dichromatic stage and has a shift towards the red on the red/green equation. The dark adaptation results show slight losses in both eyes. These results emphasise once more the sensitivity of colour vision changes prior to detectable changes on other tests.

13. Miscellaneous Macular Lesions/



P/N Anomaloscope



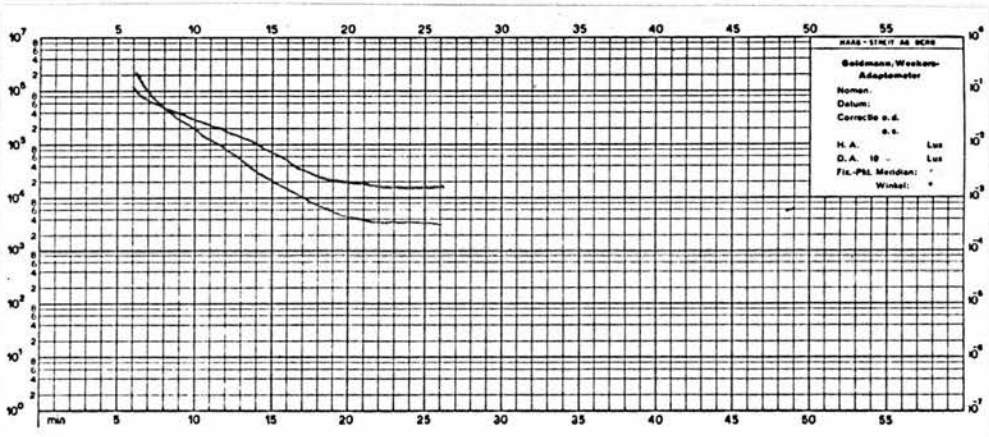


Figure 147 Macular Lesion

13. Miscellaneous Macular Lesions

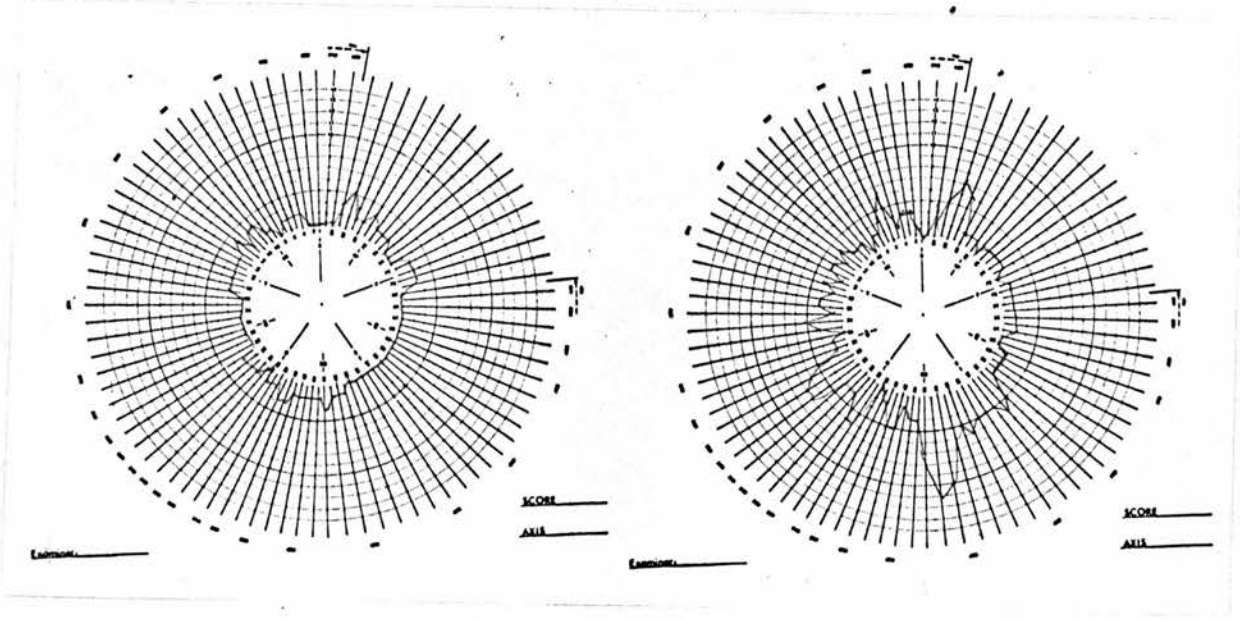
A group of 28 eyes was examined on the test battery. The interrelation between the tests is again the major concern as several conditions are included in the sample.

Results

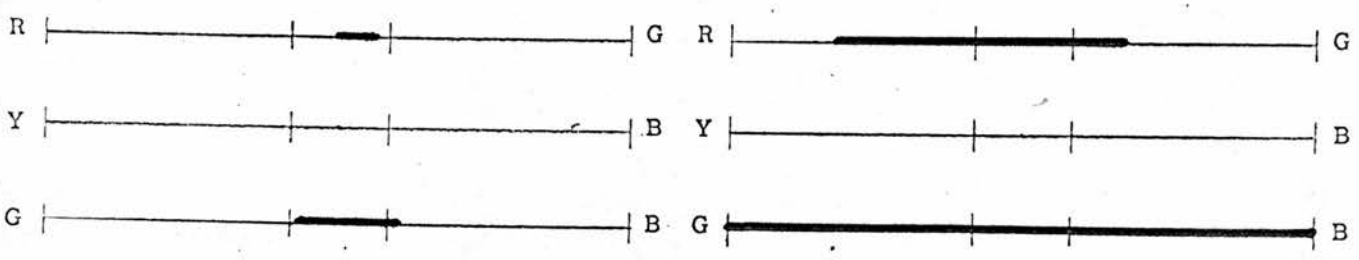
The first subgroup consisted of 12 eyes with macular degeneration. A mixture of colour vision and dark adaptation results was observed. The condition appeared to give rise to principally colour vision losses (of the blue/green type) with dark adaptation affected at a later stage. In two of the eyes both colour vision and dark adaptation were normal. A further six eyes had normal dark adaptation but abnormal colour vision, which was particularly apparent on the blue/green equation. However it also manifested itself on the 100 hue test as indicated in Fig. 147 where a tetartanopic profile is shown. Anomaloscopic red/green discrimination was normal and the blue/green equation was already dichromatic. In only two eyes out of the 12 was dark adaptation abnormal. In these cases although the anomaloscope also indicated abnormal colour vision the 100 hue profile was normal.

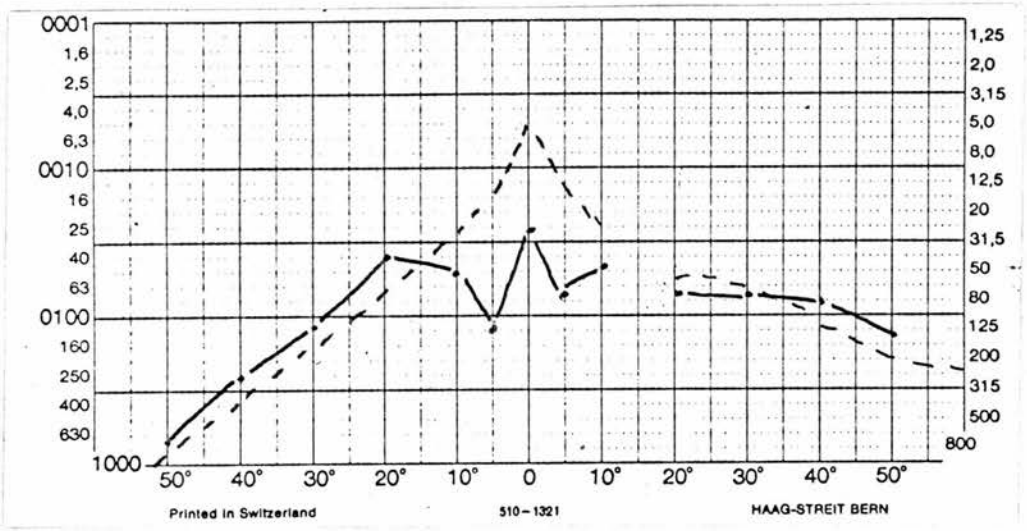
Two patients with circinate retinopathy were tested. Both showed abnormal colour vision and dark adaptation results indicating both scotopic and photopic losses.

In a patient with choroidal sclerosis and/



P/N Anomaloscope





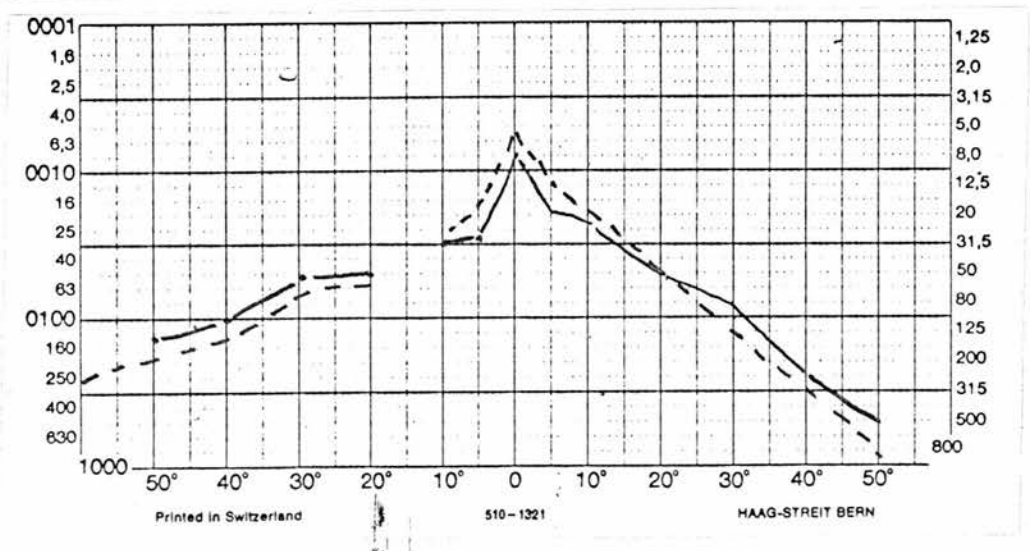
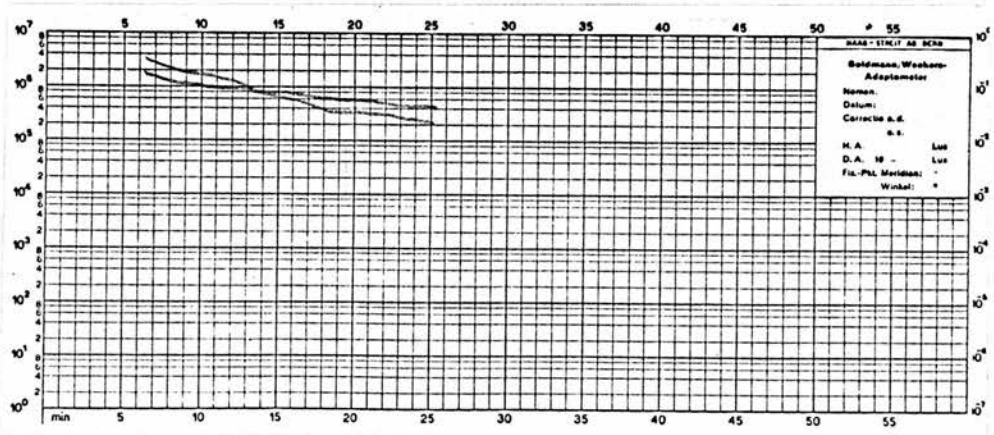


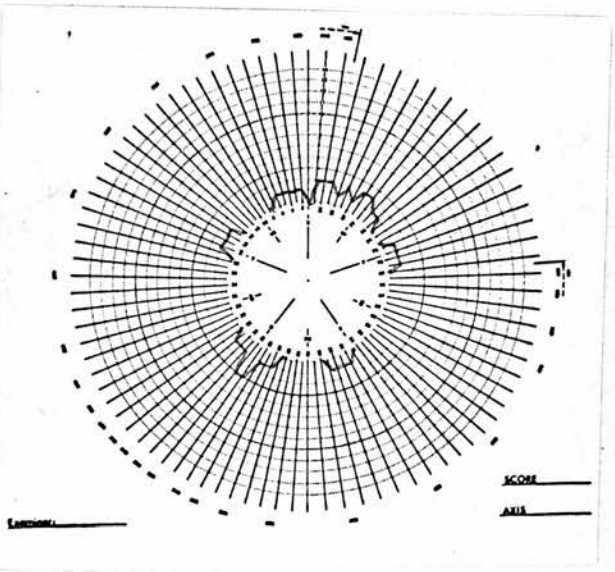
Figure 148

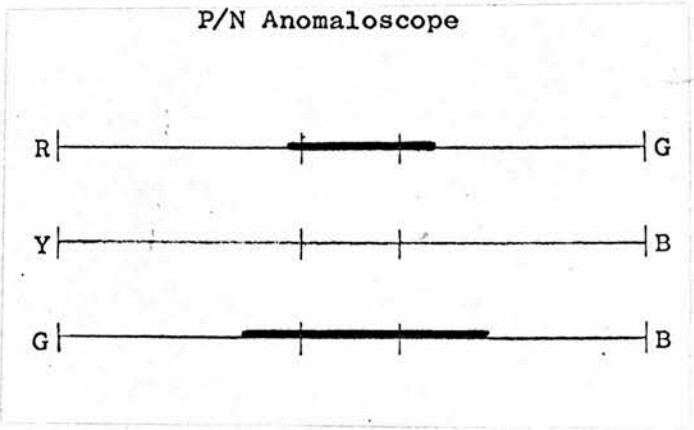
Colloid Bodies and Pigmentary Disturbance

and pigmentary degeneration visual acuity and colour vision on the 100 hue test was normal. The dark adaptation was grossly abnormal with no scotopic function and the anomaloscope showed principally yellow/blue and blue/green losses. There was an additional shift towards the red on the red/green equation which was confirmed by a reduction in the photopic luminosity curve at the red end of the spectrum on the Helmholtz colourimeter. The patient was examined two years later. Both the anomaloscopic and 100 hue colour vision results, and dark adaptation profile were found to be identical with those on first testing.

Finally, a group of patients with colloid bodies and additional pigmentary disturbance were tested. All patients had classical yellow/blue and blue/green losses with an occasional patient showing a red/green shift. An example of a comparison between the affected and unaffected eyes is shown in Fig. 148 . Visual acuity was normal in both eyes and dark adaptation in the affected eye showed only minor losses with a slight raising of the scotopic thresholds. The figure shows a comparison between static perimetry, the anomaloscope, and the 100 hue results. Although the blue/green equation is dichromatic the extension and shift towards the red on the red/green equation is most pronounced. Note that this loss in red/green discrimination/







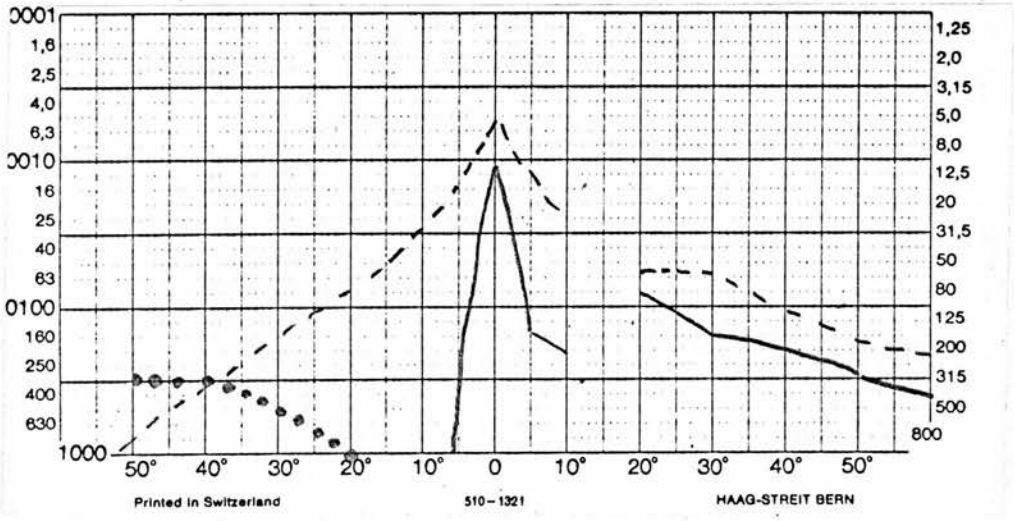
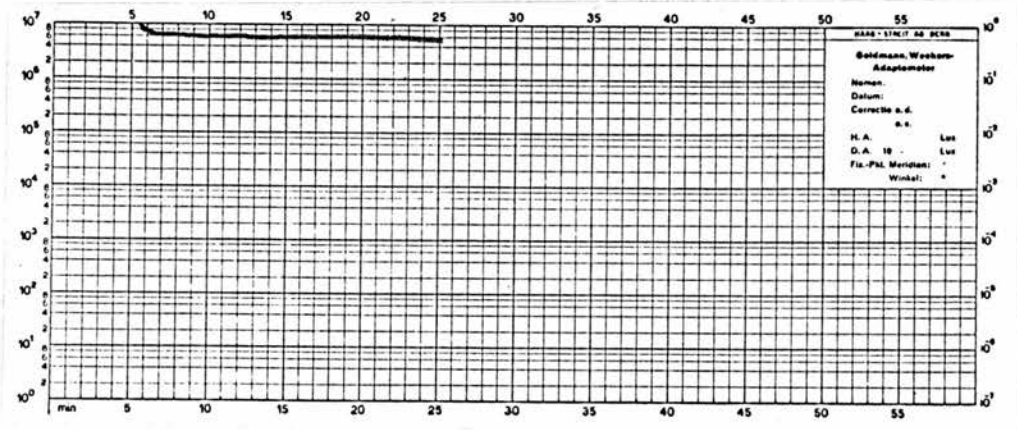
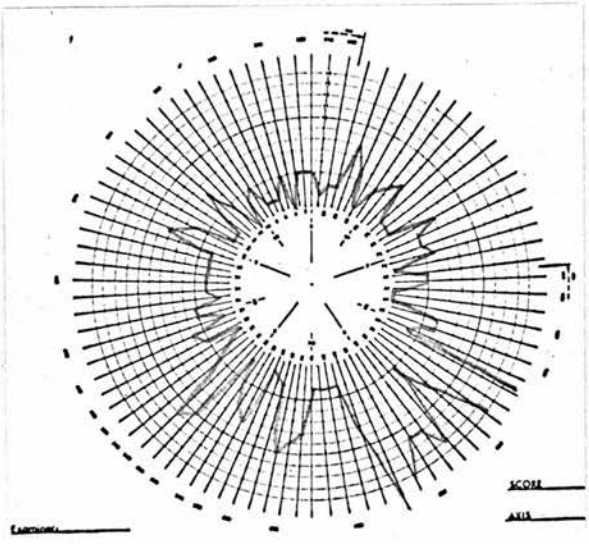
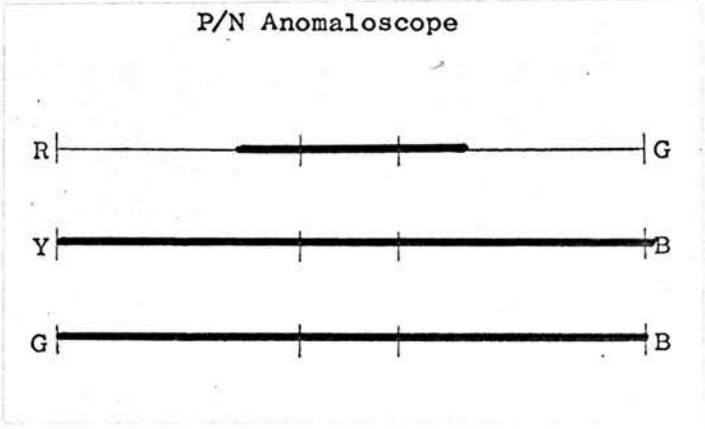


Figure 149 Heredo Tapeto Retinal Abiotrophy







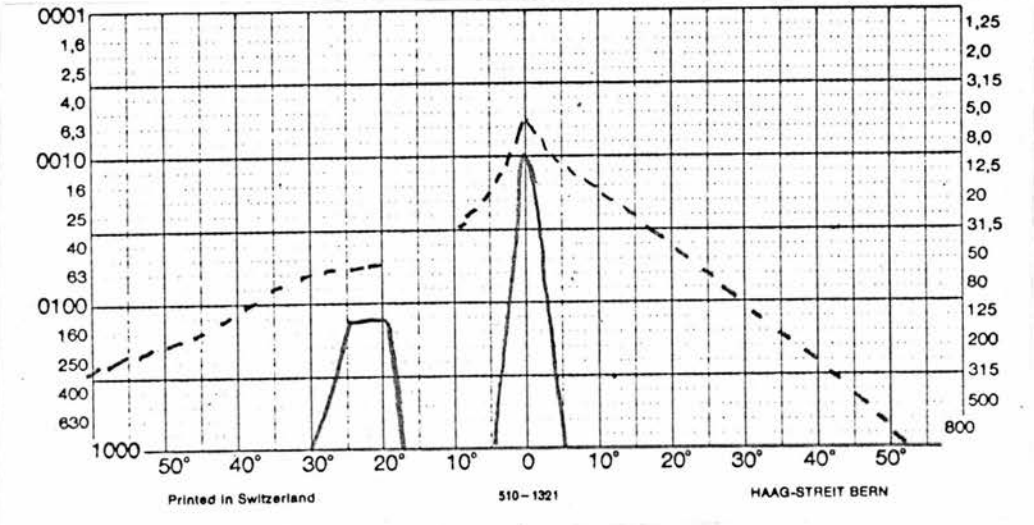


Figure 150 Heredo Tapeto Retinal Abiotrophy

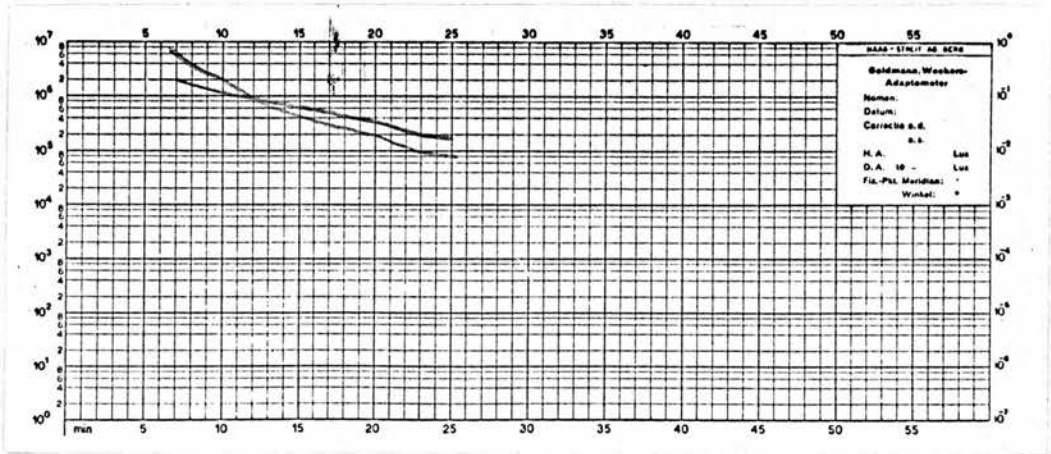
discrimination can occur whilst the 100 hue test shows only tritanopic losses.

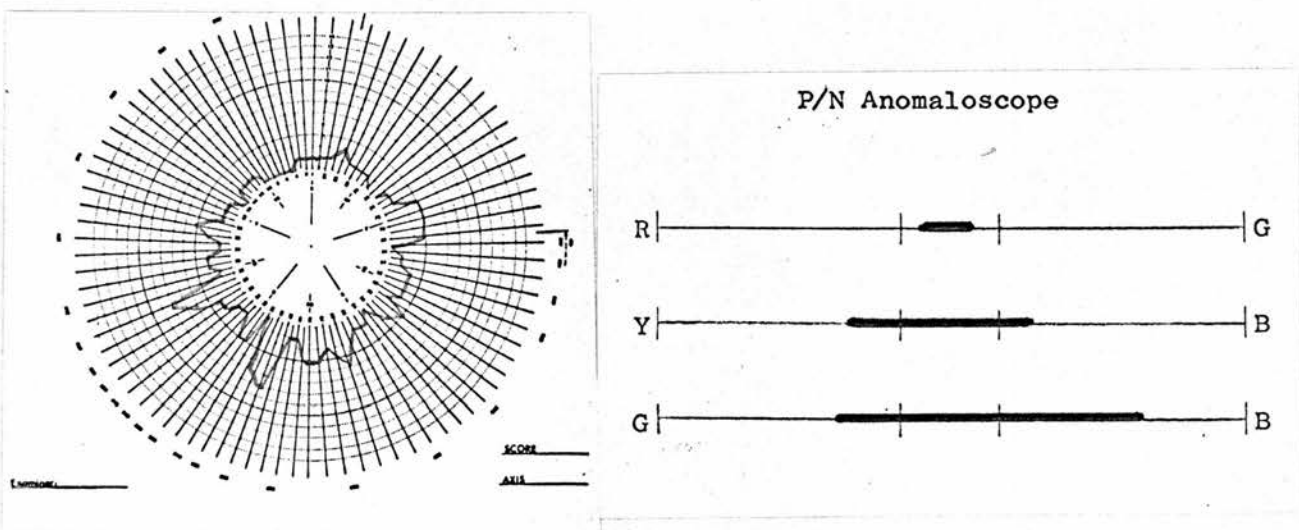
14. Heredo Tapeto Retinal Abiotrophy

Two generations of a family with this condition were studied. Eight individuals were tested, two males and two females in one generation, and three males and one female in a second generation. There was a family history of night blindness affecting both males and females around the age of 50 years.

Results

The first results are for the four children (two male and two female) of three brothers. All were aged between 45 and 65 years. The dark adaptation results for three subjects showed no scotopic function and thresholds raised over 2.5 log units. The fourth subject showed some scotopic function, but thresholds raised by 1.5 log units. The results of this latter subject and one subject without scotopic function are shown in Figs. 149 and 150 . Note in Fig.149 that the 100 hue colour vision is good in the individual where some scotopic function remains. However the anomaloscope shows red/green and blue/green losses beyond the normal limits. The red/green equation has been affected relatively early as the blue/green vision is still far from the dichromatic stage. The static perimetry illustrates clearly the nature of visual loss. It is particularly a condition affecting the nasal field, and/





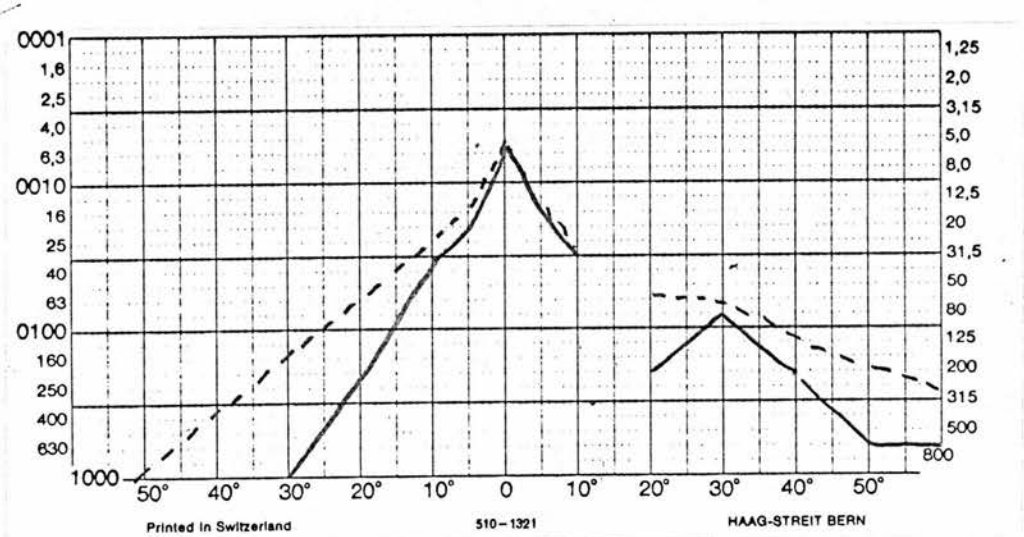
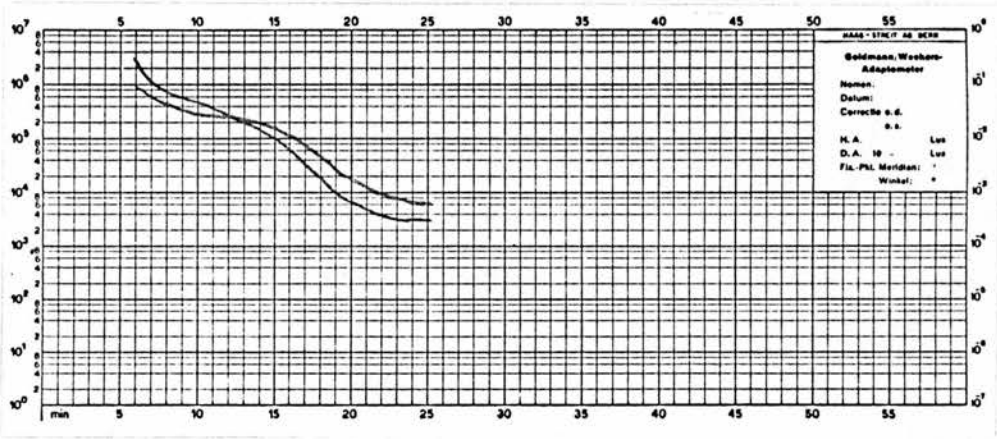
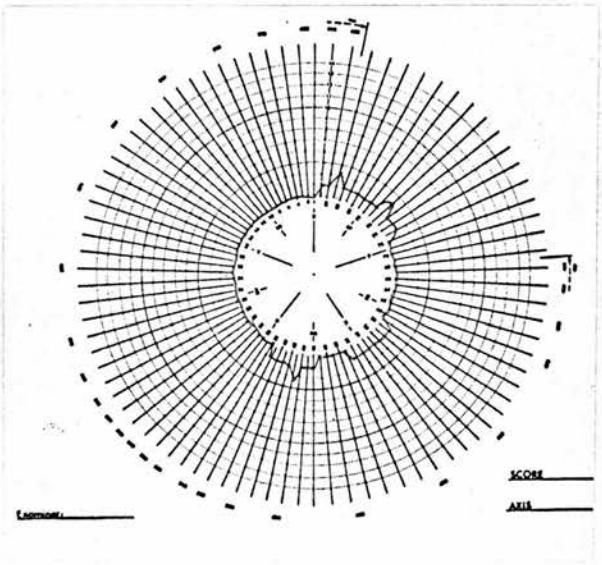


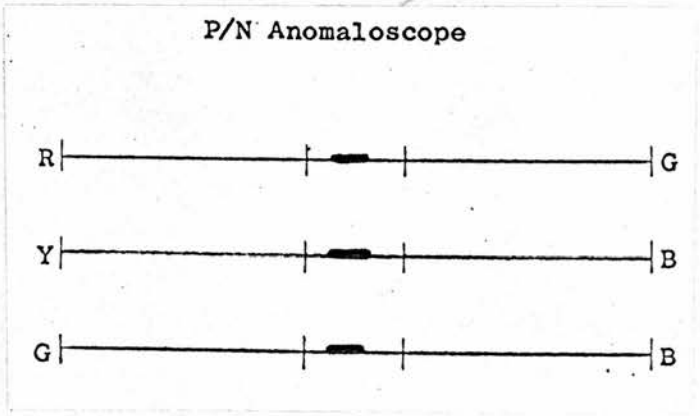
Figure 151 Heredo Tapeto Retinal Abiotrophy

and the location of greatest disturbance appears to be from 10 to 20° in the nasal field (note the slope of the gradient to the large 4 mm^2 target; the $\frac{1}{4}$ mm thresholds are all off scale in this area apart from at 50° excentricity). There are also losses appearing in the temporal field, particularly at 5 and 10° excentricity. Fig.150 illustrates more pronounced losses. The anomaloscopic losses have reached the dichromatic stage on blue/green and yellow/blue and the red/green losses are now more extensive (23 j.n.d.'s in comparison with 12 j.n.d.'s in Fig. 149). The 100 hue test is now affected with an abnormal error score and a suggestion of a red/green axis. The static perimetry in this subject is also more pronounced with only two islands of vision remaining around the fovea and in the temporal field.

In the four subjects of the next generation, age range 25 to 35 years, all had normal acuity and full Bjerrum fields and three had normal dark adaptation. A fourth subject had already dark adaptation losses of the order of 1.5 log units. This subject (female) is contrasted in Figs.151 and 152 with the results on her brother. Note that the brother (Fig.152) has excellent visual function on all tests. In contrast Fig. 151 shows the generalised dark adaptation losses. The colour vision results in this individual show yellow/blue and blue/green losses but not as yet red/green losses. The/







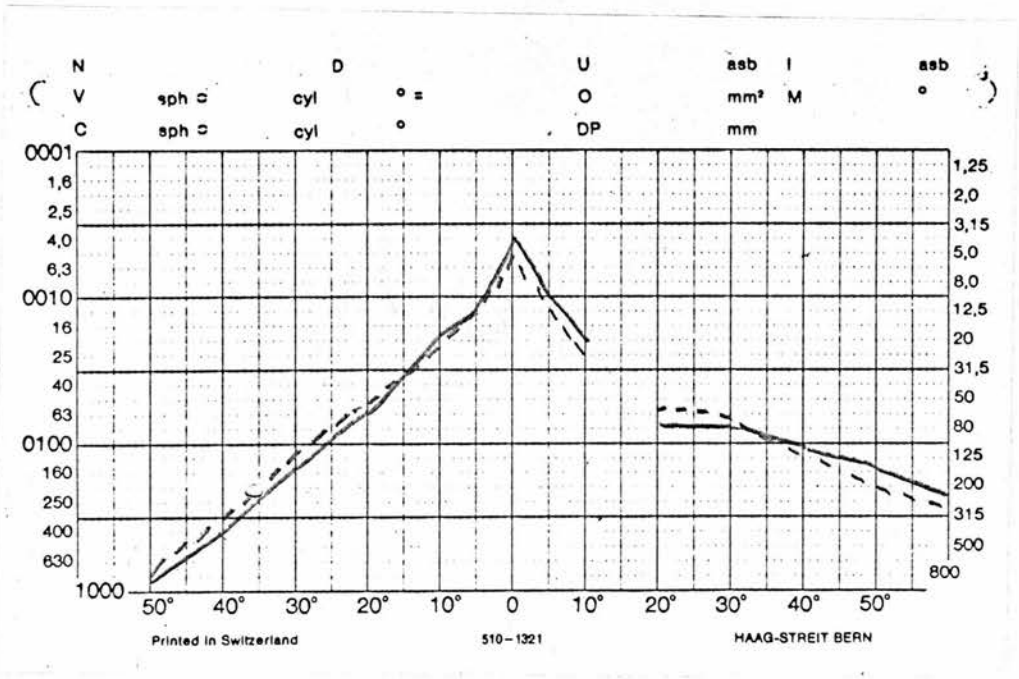


Figure 152 Heredo Tapeto Retinal Abiotrophy

The 100 hue score is on the borderline of normality. Perhaps the static perimetry data gives the best indication in this family of the stage of deteriorating vision. The losses are apparent particularly as the extremes of the nasal field.

Discussion

The results indicate the usefulness of a test battery in detecting visual loss. The static perimetric profile indicates a condition which particularly affects the nasal field. Central vision is only reduced by 0.3 log units when large scotomas are apparent in the peripheral field. However dark adaptation in a central region indicates that rod losses are apparent although the perimetric function in this area is normal. Although the foveal increment threshold is normal, there are colour vision losses at a relatively early stage of the condition. The yellow/blue dyschromatopsia is the most sensitive of the colour vision mechanisms to change, but red/green vision is also affected at an early stage of the condition before the total loss of scotopic function in a central area and before the dichromatic stage of the yellow/blue dyschromatopsia is reached.

15. Toxic Amblyopias

(i) Tobacco and Alcohol

Dyschromatopsias of the red/green type are most frequently reported in this condition RIZZO (1955);/

(1955); FORSTER (1959); CHISHOLM (1968). However Verriest reports in addition to a type II red/green dyschromatopsia, extended yellow/blue losses and a dyschromatopsia without axis.

Results

In the three patients studied, the colour vision defects were extensive with 100 hue error scores around 600. The anomaloscope showed pronounced red/green and yellow/blue losses and static perimetry indicated central scotomas to white light. Clearly the losses in these patients were already at an advanced stage when tested.

(ii) Chloroquine

Results by DAVENPORT and LAKOWSKI (1968) showed patients on Chloroquine had losses in the tritan region of the 100 hue test.

Results

Two patients were tested. Both had visual losses of the yellow/blue type on the anomaloscope while red/green vision appeared to be unaffected.

(iii)Ethambutol

This is a highly effective anti tuberculous agent, but has been associated with the significant ocular side effect of retrobulbar neuritis CARR and HENKIND (1962). This association is dose related LEIBOLD (1966).

In the present study two groups of patients were studied. The first group, (a), consisted of 15 patients/

patients who were on different doses of Ethambutol. The second group, (b), was established to study the effects of Ethambutol over a period of time. Patients in an experimental group were on a daily dose of 20 mgm./kg and 200 mgm. Isoniazid. A control group was established in which PAS and Isoniazid in doses of 20 g. and 200 mgm respectively were given. The experimental and control groups represented standard anti tuberculous chemotherapy. The dosage was sufficiently low to be only rarely associated with retrobulbar neuritis.

Results

(a) The patients were tested on the Ishihara, the 100 hue test, dark adaptation and foveal differential threshold.

In the first group of 15 patients, the mean scores were compared with those of age controls. The mean dark adaptation scores were not significantly different from the normals indicating scotopic function was normal in the group. (Only one patient had raised scotopic thresholds). The foveal differential threshold was abnormal in 5 out of the 15 patients. The mean 100 hue error score of the group was significantly different from normal with the mean score falling at the 90th percentile of the normal population. The majority of profiles were anarchic. The Ishihara also showed cases of abnormal error scores.

It appeared, therefore, that a small group of patients/

patients on Ethambutol did have significantly affected colour vision but normal dark adaptation. However as many patients in the group had had in the past a variety of treatments, it was not possible to establish whether it was the athritis, Ethambutol, past treatment, or interaction between these that had produced the visual loss.

(b) The second study consisted of eighteen eyes tested before therapy, at 3 months following the prescribed treatment, and 6 months later. Half the patients were on an Ethambutol regime (Ethambutol and Isoniazid) and half were on an alternative regime (PAS and Isoniazid). The allocation of drugs to patients was made on a random basis. One person required a change of therapy midway through treatment but the remaining patients maintained their course of treatment.

Dark adaptation results showed no significant difference at 3 months or at 6 months from the pre-treatment curve. Most scotopic function results (under either regime) were normal. Only two patients had raised scotopic thresholds. These were apparent before treatment began and remained at the same level (raised 1.5 log units) throughout treatment. Similarly no change was found in the foveal differential threshold test.

The mean group 100 hue score prior to treatment was 142. This was again close to the 90th percentile score/

score of the comparable normal group. It was evident therefore that the patients before beginning therapy had generalised colour vision losses. The two drugs were assessed at 3 months by obtaining the difference between the 3 month score and the pretreatment score for each patient. The mean of these differences was found.

For Ethambutol and Isoniazid the mean group difference was - 7.0

For PAS and Isoniazid the mean group difference was - 16.0

Neither of these figures was significantly different from each other or from zero. A similar comparison of the pretreatment scores and scores after six months showed:-

For Ethambutol and Isoniazid a mean group difference = + 6.2

For PAS and Isoniazid a mean group difference = - 8.3

Neither figure was significantly different from each other or from the zero level.

It should be mentioned that one individual in the group showed a significant rise in 100 hue error score on Ethambutol (from 42 errors to 73 errors at 3 months to 134 errors at 6 months). However the group scores as a whole were not affected by the administration of either drug. It has been reported that Isoniazid produces/

produces a red/green dyschromatopsia, VERRIEST (1964). There was no indication of this under present test conditions.

Summary

Arthritic patients on Ethambutol were found to have higher 100 hue error scores than the normal population. However in a study over a time interval of 9 months, an intra individual comparison of results showed that colour vision was not significantly affected by the drug. The drug was administered in conjunction with Isoniazid, as this combination formed the standard anti tuberculous chemotherapy. The control group (PAS and Isoniazid) produced no significant visual losses.

The 100 hue error profiles were mainly anarchic and only rarely was a tritan axis seen. The general results suggest that patients on Ethambutol do have colour vision but not dark adaptation losses, but that Ethambutol does not lead to further deterioration in vision.

(iv) Flurbopruphen

Twelve patients were tested on the 100 hue test and foveal differential threshold at three intervals each 3 months apart.

The mean score of the group (97) was not significantly different from the normal population.

An assessment of the effect of the drug was obtained by finding the difference for each individual between the first score, the 3 month score and the 6 month scores./

scores. The mean of the difference between the first and the 3 month scores was + 0.5. The mean of the difference between the first and the 6 month scores was - 5.0. As the standard deviation of the differences was 25, it is clear that neither difference was significant. It may be concluded therefore that within the experimental conditions no change in visual discrimination is brought about by the administration of Flurbopruphen.

16. General Discussion

A sample of 193 eyes with a variety of conditions has been examined in Section d. The results indicated different patterns of test scores in different conditions. However there was a surprising uniformity about the results of the yellow/blue and blue/green anomaloscope equations between different groups. Losses in discrimination on these equations were found in nearly all the cases examined, including those conditions in which red/green dyschromatopsias have generally been associated. Consequently there was no condition in which only a red/green dyschromatopsia was found. Similarly there were no patients who had an acquired red/green dyschromatopsia without concomitant yellow/blue or blue/green dyschromatopsias. This was a distinguishing feature of acquired dyschromtopsias in contrast to congenital dyschromatopsias. On the other hand there were several instances among the patients where only/

only yellow/blue or blue/green dyschromatopsias were found.

Both scotopic and photopic losses appeared independently of each other but there was often a correlation between yellow/blue or blue/green and scotopic losses. The earliest type of change was most frequently detectable on the yellow/blue and blue/green anomaloscope equations. For instance the 100 hue test was often normal when large yellow/blue losses were present on the anomaloscope. The 100 hue test also showed a tritan profile when extensive red/green losses (in addition to yellow/blue losses) were found on the anomaloscope.

In dark adaptation, early cross over times were only seen in cases where the scotopic function was normal. On the other hand late cross over times were generally associated with scotopic losses and were seen as a stage towards total loss of scotopic function.

These results have important applications to hypotheses on the pathogenesis of acquired dyschromatopsias. It will be recalled that the results of the German school showed that lesions at the deep retinal layers resulted in yellow/blue dyschromatopsias, and lesions at the ganglion cell and beyond gave rise to red/green dyschromatopsias. These findings, summarised in Koellners' Rule (1912), were in general confirmed by more recent research workers. Any subsequent qualifications/

qualifications to the rule have been in terms of further differentiation so that for instance VERRIEST (1964) writes "the conditions of the deep layers of the retina can give rise not only to a defect of the yellow/blue axis but also to a special type of defect of the red/green axis (type I). The defect of the yellow/blue axis seems to be above all due to peripheral and hemeralopigenous conditions being accompanied by a particular suffering of the rods while type I defect of the red/green axis seems to be conditioned by the more macular and nyctalopigenous conditions due to a selective damage of the cones. This schema allows us to localise very presumptively of course the lesions which cause visual defects in certain conditions whose anatomical pathological substratum is unknown or difficult to interpret". This further differentiation reinforces the possibility of using the rule to relate types of dyschromatopsia to the site of lesions, and would certainly be a desirable outcome of researches on acquired dyschromatopsias. However in the present results the rule is questioned, not only because instances have been found which require further modification to the rule, but because the basis for recognising either a red/green or a yellow/blue dyschromatopsia has been shown to be uncertain. Although the results on certain tests correlate (e.g. the yellow/blue and blue/green anomaloscope equations) and therefore show agreement in/

in their ranking of individuals and assessment of dyschromatopsias, other tests (e.g. the 100 hue test and anomaloscope) do not. Consequently the 100 hue test might indicate a normal profile (i.e. a normal balance between red/green and yellow/blue discrimination) while the anomaloscope might indicate pronounced losses in the yellow/blue system, but a normal mechanism for red/green discrimination.

The lack of significant correlations between tests which measure discrimination along different axes in CIE space would be expected from the physiological evidence of different mechanisms underlying red/green and yellow/blue discrimination (see Section III). However it is the lack of correlation between tests measuring along the same axis in CIE space which is the problem. When this occurs, the ordering of individuals within the normal distribution varies from one test to another so that the relative Z scores (or the basis for assessing a dyschromatopsia) also vary.

It seems therefore that there are two questions to be answered before an application of the rule. Firstly if red/green and yellow/blue dyschromatopsias are test dependent, how shall we determine their existence? Secondly once this is determined how shall we compare the two? The statistical procedure outlined on page 185 goes part way to answering the first question as it establishes the limits of the normal population scores/

scores for a particular test. However it cannot resolve the problem of what constitutes a dyschromatopsia when it is operationally defined in terms of this test or that test. The traditional answer to the second question is also statistical as it uses the population distribution as the common denominator between the red/green test and the yellow/blue test. However comparisons between the two types of dyschromatopsia are still qualifed in the form "the red/green dyschromatopsia (Z score) on test x is greater than the yellow/blue dyschromatopsia (Z score) on test y, therefore we are entitled to call this predominantly a red/green dyschromatopsia". (Note that the problem is still present even if one Z score is within the criterion score for a normal population and the other Z score is outwith its criterion score). These problems could be resolved by general agreement on standardisation of tests and on the methodology of testing.

In the present work an attempt has been made to overcome these problems on the Pickford Nicholson Anomaloscope by providing a common background in a uniform chromaticity scale and a common methodology of testing across different anomaloscope equations. Here it is assumed that the j.n.d. is the link between discrimination along the red/green or yellow/blue axes. However when population distributions are plotted on the uniform chromaticity scale both the means and standard/

standard deviations of the anomaloscope equations in j.n.d.'s are still slightly different in the youngest age group which was originally used for the definition of the j.n.d. at different CIE locations. Nevertheless this represents a move towards a solution. On the basis of the new system applied to the anomaloscope, Koellner's rule requires modification towards the recognition of one type of change in which the anomaloscope yellow/blue or blue/green equations are altered to reach the dichromatic stage before any red/green losses are apparent. (This corresponds to the acquired yellow/blue dyschromatopsia) and secondly a change which occurs on both the red/green and yellow/blue or blue/green equation so that the red/green equation is abnormal when yellow/blue discrimination is abnormal but still trichromatic. (This corresponds to the former red/green dyschromatopsia). The distinction between a red/green type I and type 2 dyschromatopsia would be modified on the uniform chromaticity scale towards one type of loss in which a shift towards the red end of the spectrum did occur (i.e. loss of red sensitivity) and a second type of loss in which an extended matching range was apparent with equivalent losses in both red and green mechanisms (i.e. no shift in mid matching point).

VII SUMMARY AND CONCLUSIONS

The general results and conclusions from this study are as follows:-

1. A review of the psychophysical methods which are used to obtain evidence on visual function showed that several methods in common use are contaminated by extraneous or non-sensory variables. These variables operate on the response criterion adopted by an observer in the test situation. New techniques were outlined which provided an independent assessment of both the response criterion and of sensory discrimination. By use of these methods doubt has been cast on the assumptions underlying a sensory threshold. The final choice of method depends upon the accuracy the experimenter desires from his data and the range of visual function in the population he is studying. However if possible the signal detection methodology should be used in preferably the forced choice or rating scale paradigm as it is the only method allowing observer sensitivity per se to be isolated from psychological variables which determine the response criterion. This method is recommended in the study of visual differences in sensitivity within the normal population, or in the assessment of early changes in sensitivity brought about by ageing or by clinical factors. If the/

the experimental situation does not require such finesse, then of the classical methods that of constant stimuli is recommended next, followed by the method of limits. Instances of the practical effects of methodology are given in the Section on Ageing and in the Glaucoma study. In both cases it was shown that the significance of the results can hinge on the methodology in the test procedure. The signal detection methodology was more sensitive in the detection of abnormal threshold values, and the variance of normal population results was reduced by the method. No significant correlation between the forced choice and the conventional perimetric method of limits was obtained between individuals falling within the 'normal' range. However significant correlations between the two did exist when abnormal values were included in the sample, so that both methods correlated with the common factor of deterioration.

2. Physiological and Psychophysical evidence on normal vision was given as a background to colour vision anomalies. These were discussed for congenital dyschromatopsias and acquired dyschromatopsias. The latter was divided into clinical effects, and ageing effects on colour vision and on general function.

3. The development and assessment of tests were carried/

carried out for a.) macular function and b.) general function. Tests were assessed in the context of physiological mechanisms and of the CIE system.

a.) Conclusions regarding the Snellen acuity test and the Pseudo Ishochromatic Plates were:-

Perception is governed by complex factors which go beyond the optical components in the test. As a result tests using letters or symbols differ in legibility despite the optometric principle. Visual acuity is defined operationally so that there are as many tests as test objects. Thus results from one acuity test are not transferable to another. The Ishihara test is principally a test of red/green defects while the AOHRR has plates for both red/green and yellow/blue defects. Although the AOHRR plates differ in the degree of difficulty the Ishihara is principally a dichotomous test between normal and abnormal vision. It is more meaningful to regard the error scores as an indication of the probability of an individual belonging to different categories.

The Farnsworth Munsell 100 hue test is useful for both congenital and acquired defects. Box (85 - 21) is the easiest and box (43 - 63) the most difficult. A test procedure was recommended which included randomising the cap presentation; the test presentation for right and left eyes; and the scoring method. Age norms and illumination effects/

effects were considered. Simulated macular pigmentation effects produced a tetartanopic confusion axis. Significant differences between an experienced and an inexperienced group were found. Those individuals making greater than average errors without filters made above average errors when wearing filters. Selective absorption of certain wavelengths affected test performance more than changes in luminance. The upper limit of non random cap arrangements was 984 for the total test and 200 for any box. Particular consideration to this information should be given when either the test is used clinically or children are tested who do not have a developed concept of serial arrangement.

The Pickford Nicholson anomaloscope was assessed. A transformation of the anomaloscope scale was carried out by means of the CIE UCS 1960 u.v. space. This provided a linear visual scale for any colour equation and provided a basis for comparisons across equations. Age norms were established for the new scale.

The Helmholtz Colour Mixer was modified for flicker measurements of the photopic luminosity function. The instrument acted as a spectrophotometer for transmission measurements of filters. The photometric scale was in terms of voltage intensity relations. The voltage intensity relation at one/

one wavelength was shown to be deducible from that at other wavelengths. Photopic luminosity measurements on normals and on congenital colour defectives were in general agreement with VERRIEST (1971). Deficiencies in the CIE $V\lambda$ curve at short wavelengths were noted. Age effects rotated the luminosity curve so that the relative sensitivity to blue was decreased and the relative sensitivity to red was increased. Norms were established for $V\lambda$ determination, and wavelength discrimination at 590 and 496 nm.

b.) The general function tests were static perimetry in a horizontal retinal meridian and dark adaptation. An assessment of the factors influencing the retinal threshold gradient was followed by age norms for the Standard Goldmann conditions (31 asb.). Norms were established for the sensitivity at selected retinal points and for the rate of change in sensitivity between points. Some problems of spatial summation were assessed. A new light source was fitted to the standard instrument for increment threshold measurements against a high intensity background luminance. Experiments were carried out to assess whether peripheral thresholds at the high luminance were predominantly cone responses. Increment thresholds to different wavelengths against different bowl/

bowl luminances were carried out following high preadaptation, and against zero luminance following preadaptation to different bowl luminances. Norms were established for high intensity adaptational conditions and for scotopic background conditions.

The Dark adaptation process and the variables which affect it were assessed. Modifications to the basic dark adaptation experiment were made. These included automation of the recording system, and adjustments to the preadaptation source, fixation spot and test patch. A two filter analysis of the dark adaptation process was developed which delineated the cone and rod segments and emphasised the transition point between the two. This was possible by use of two test patch filters one with maximum transmission at the photopic luminosity peak, and one with maximum transmission at the scotopic luminosity peak. A single preadaptation period preceded the sensitivity measurements so that the time required for testing was no longer than in conventional dark adaptation methods. Norms were established for the absolute level of blue/green and yellow thresholds at any point up to the 20th minute following preadaptation, and for the characteristic separations between the curves during rod and cone vision and the age effects on transition times (which were significant).

4. In a study of diabetes, blue/green colour discrimination/

discrimination was most affected and was most closely related to retinal state. This finding was supported in a follow up study of diabetics without retinopathy in which Bayesian statistics were used to predict the likelihood of retinopathy developing in a 5 year period. This was successful using the duration of diabetes and the blue/green matching range as predicting variables. In addition to blue/green deterioration there was evidence of significant changes on many visual function tests, including dark adaptation and static perimetry, in diabetics with no retinopathy. The dark adaptation thresholds were raised but the only significant difference was in the early transition time in diabetics. Perimetric data at high luminance showed significant reductions particularly in the temporal field. Irregularities in the threshold gradient were observed together with a general reduction of vision in some patients, a peripheral loss in some patients and a central loss in some patients. A factor analysis showed that ten factors were necessary to account for the variance in the data, in comparison with forty-five original variables. Tests designed for measurement of rod and cone function loaded on orthogonal factors. Also some red/green discrimination tests and some yellow/blue discrimination tests loaded on orthogonal/

orthogonal factors, indicating a different underlying source of variance and reinforcing the idea that different mechanisms were responsible for these visual functions. However the striking feature of the analysis was that it was the tests which tended to determine the factors rather than similar variables across different tests. It appeared therefore that the way in which the data was collected was very important in the association of variables. This evidence strongly supports the notion of operational definitions in visual function testing and furthermore supports the use of a test battery. There was a close association between losses in sensitivity to blue and early dark adaptation transition times. This supported the hypothesis of rod-blue cone linkage and suggested the inhibition of rod function by blue cones.

5. A study of potential glaucoma patients showed the psychometric function covered a range of 0.6 log. units under scotopic conditions and 0.5 log units under photopic conditions. Pupil diameter appeared to be a factor in the determination of scotopic values but was unrelated to photopic thresholds. Age correlated with threshold values under both conditions and also with intra ocular tension. Scotopic and photopic thresholds at the same retinal point were related when abnormal thresholds were/

were included but unrelated when thresholds within the normal range were compared.

In a study of potential glaucoma patients and in a study of patients with chronic simple glaucoma in which the unaffected eye was tested, approximately half the patients had abnormal threshold values under either scotopic or photopic conditions or both. There was no unique pattern of losses suggested by either group. Several patterns occurred with scotopic or photopic losses occurring in isolation or together in a mixed functional loss. It is not known which type of loss is characteristic of glaucoma although it is generally believed that rod losses are prevalent and might represent the first signs of deteriorating function, ZUEGE and DRANCE (1967). As reported in 1.) the forced choice method detected more 'abnormal thresholds' than conventional methods and did not correlate with conventional techniques for those patients within the normal distribution curve.

6.) In a study of patients with retinitis pigmentosa the functional results showed gross abnormalities on all tests with blue/green vision most affected. Two types of change were apparent in dark adaptation with either early or late transition times. The early cross over time was associated with only blue/green and yellow/blue losses (see 4.) whereas the/

the late crossovers had additional red/green defects. Scotopic losses were more extensive than photopic losses. In general the psychophysical tests correlated highly with each other but there were relatively few significant correlations between psychophysical and electrodiagnostic measures. An analysis of the anomaloscope equations supported the hypothesis that blue/green defects occurred at an early stage in the disease with red/green defects occurring at a later stage.

A comparison of structural and functional changes showed that functional abnormalities are more extensive than structural abnormalites in the foveal region. This applies to any measure of visual function included in the test battery. The percentage of cases with functional abnormalities ranges from 75% on visual acuity and on the 100 hue test, to 95% on the blue/green matching range. The structural abnormalities are present in 50% of cases. Correlations between function and structure indicate that Snellen visual acuity and the 100 hue test correlate with structural changes in both the central and peripheral regions of a 20^{o} circle centred on the fovea. On the other hand blue/green discrimination and dark adaptation are only significantly associated with structural changes in the peripheral zones of this region, and red/green/

green colour discrimination and the foveal differential threshold are only significantly correlated with structural changes in the central zones of this circle around the fixation point.

7.) The results on a miscellaneous group of conditions indicated different patterns of test scores in different conditions. However there was a surprising uniformity about the results of the yellow/blue and blue/green anomaloscope equations between different groups. Losses in discrimination on these equations were found in nearly all the cases examined, including those conditions in which red/green dyschromatopsias have generally been associated. Consequently there was no condition in which only a red/green dyschromatopsia was found. Similarly there were no individual patients who had acquired red/green dyschromatopsias without concomitant yellow/blue and blue/green dyschromatopsias. On the other hand there were several instances among patients where only yellow/blue and blue/green dyschromatopsias were found. The earliest type of change was most frequently detectable on the yellow/blue and blue/green anomaloscope equations, and the 100 hue profile was often normal when large yellow/blue losses were present on the anomaloscope.

Both scotopic and photopic losses appeared independently but there was often a correlation between yellow/blue or blue/green and scotopic losses. Early/

Early cross over times were only associated with normal scotopic function while late cross over times were generally associated wtth scotopic losses and were seen as a stage towards total loss of scotopic function.

8.) A general perspective of the work would suggest that the lack of correlation between visual function tests was a more common occurrence than positive correlations between tests. This may in part be due to methodological problems. Even when photometric and colourimetric analyses show that two tests are designed to measure the same underlying physiological mechanism, it is possible for the methodology of testing to be the determining factor in whether the tests correlate or not. There was evidence in factor analysis of a red/green factor orthogonal to a yellow/blue factor and a scotopic factor orthogonal to a photopic factor. Tests which correlated to form factors tended to have the same methodologies. The variety of results in Section VId. supported the general factor analysis picture of tests loading on factors and consequently operational definitions of visual function. Because of this there are problems concerning the application of Koellner's rule. An attempt towards a solution was made by the transformation of the anomaloscope data to the uniform chromaticity scale. On this basis the results of the study have suggested/

suggested a modification of the rule towards recognising firstly one type of dyschromatopsia where only yellow/blue or blue/green losses are present until the dichromatic stage is reached - (this corresponds to the acquired yellow/blue dyschromatopsia); and secondly a dyschromatopsia in which parallel changes occur on both the yellow/blue and the red/green equations so that the red/green equation is abnormal when the yellow/blue losses are still trichromatic - (this corresponds to the former red/green dyschromatopsia.) The distinction between the type I and type II red/green dyschromatopsia would be that the former exhibits a red shift but that the latter is more commonly seen as a symmetrical extension of the matching range about the mid-matching point when the uniform j.n.d. scale is used.

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